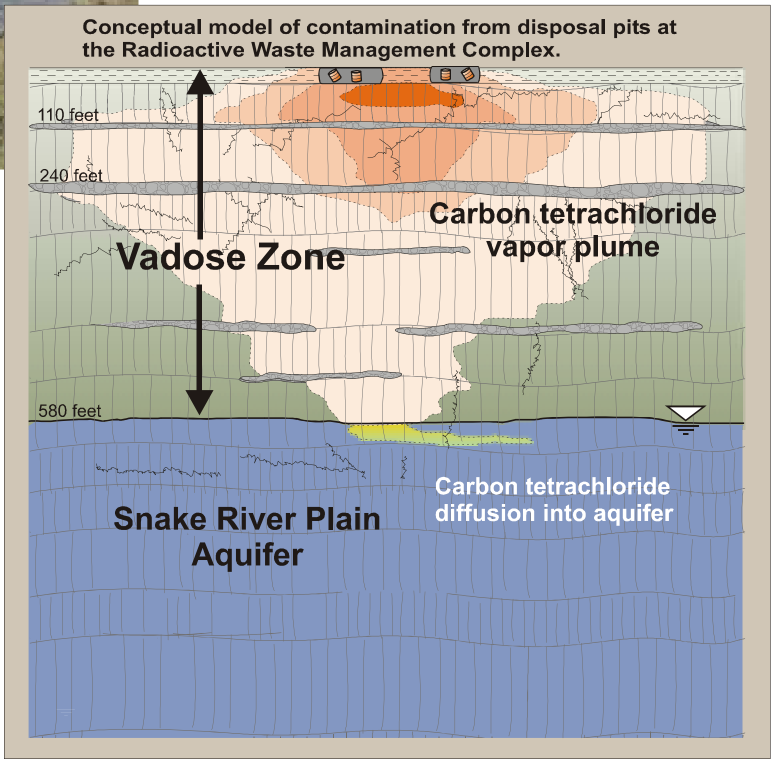
Idaho National Engineering and Environmental Laboratory

Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory



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Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory

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ABSTRACT

Subsurface contamination in the vadose zone, that portion of the subsurface pathway between land surface and an underlying aquifer, poses environmental problems at the Idaho National Engineering and Environmental Laboratory (INEEL) in eastern Idaho and across the U.S. Department of Energy complex. Assessing potential adverse impacts from these contaminated sites requires an understanding of the mechanisms controlling contaminant transport. Currently, vadose zone experts at the INEEL cannot with confidence predict the movement of water and contaminants in the complex, heterogeneous, fractured subsurface at the INEEL, especially within the vadose zone.

In the draft version (Revision 1) of the Vadose Zone Deficiencies document, deficiencies in scientific understanding of flow and transport processes in the vadose zone at the INEEL were identified and grouped into 13 categories and recommendations were provided to address each of the deficiencies. The draft document provided the basis for an INEEL Vadose Zone Workshop that was conducted October 20 and 21, 1999, in Idaho Falls, Idaho. The workshop was conducted to group and rank the previously identified deficiencies and for the subsequent development of science plans to address the deficiencies that limit reliable predictions of water and contaminant movement in the subsurface.

The workshop participants, comprising INEEL and scientists and project managers and non-INEEL scientists knowledgeable about the vadose zone, developed science- and technology-based recommendations derived through a series of technical sessions at the workshop. In this document, the final version of the Vadose Zone Deficiencies document, the draft document has been incorporated, largely intact, as well as the results from the workshop. The workshop participants grouped the deficiencies in vadose zone understanding at the INEEL into seven categories. These seven categories will be the focus areas of five science plans that are being developed to address the deficiencies. This document lays the foundation for the INEEL Site-wide vadose zone roadmap.

ACKNOWLEDGMENTS

The authors of this document acknowledge the U.S. Department of Energy Program Office of Vadose Zone Science and Technology for its support in the development of this document. The process of developing the document provided a unique opportunity for the authors to identify key deficiencies in vadose zone understanding at the Idaho National Engineering and Environmental Laboratory (INEEL) and to make recommendations to address those deficiencies within their areas of expertise.

At the INEEL Vadose Zone Workshop on October 21 and 22 in Idaho Falls, Idaho, other scientists and program managers at the INEEL and cognizant personnel off the INEEL Site provided for the authors an invaluable peer review of the deficiencies, and helped developed outlines to address the deficiencies. The scientists and program managers at the INEEL and off the INEEL Site who provided those functions at the workshop included L. S. Cahn, C. J. Craiglow, E. C. Miller, R. K. Podgorny, and K. S. Sorenson, Jr., of the INEEL; Eric L. Miller and Fernando Miralles of Northeastern University; Paul Kaplan of Sandia National Laboratories; Roy Mink, Katherine Owens, and Allan Wylie of the University of Idaho; Dennis Weber of the University of Nevada at Las Vegas; and L. DeWayne Cecil of the U.S. Geological Survey. Their contributions, based on singular expertise and knowledge of the vadose zone, greatly enhanced the quality and credibility of this document.

In addition, P. A. Tucker, technical editor, and J. M. Brower, graphic artist, are acknowledged for their significant contributions to the quality of this document.

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FIGURES

TABLE

ACRONYMS

BLT	Breach, Leach, and Transport (modeling code)
CFA	Central Facilities Area
CFU	colony-forming unit
DOE	U.S. Department of Energy
DUST	Disposal Unit Source Term (modeling code)
EDTA	ethylenediaminetetraacetic acid
ICPP	Idaho Chemical Processing Plant
IDHW	Idaho Department of Health and Welfare
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
NPR	New Production Reactor
OCVZ	organic contamination in the vadose zone
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
SIP	Subsurface Investigations Program
SL-1	Stationary Low-Power Reactor No. 1
SRPA	Snake River Plain Aquifer
TRA	Test Reactor Area
USGS	U.S. Geological Survey
VOC	volatile organic compound
WAG	waste area group

Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory

1. INTRODUCTION

Shallow land waste storage and disposal and spills and leaks from operations have resulted in subsurface contamination at the Idaho National Engineering and Environmental Laboratory (INEEL) and across the U.S. Department of Energy (DOE) complex. Assessing the potential adverse impacts from these contaminated sites requires an understanding of the mechanisms controlling transport in the vadose zone, that portion of the subsurface pathway between land surface and an underlying aquifer. Prediction of contaminant migration in the vadose zone is limited by both a lack of characterization information because of subsurface heterogeneity and a lack of critical knowledge about the impact of physical, chemical, and biological factors on transport. Furthermore, because of heterogeneity, where the mechanisms are understood, they are often poorly parameterized. The current degree of characterization and scientific knowledge is not sufficient to provide a full understanding of contaminant movement at the INEEL.

Several findings at sites across the DOE complex reveal cross-cutting deficiencies in the investigative methods, characterization technologies, and predictive simulations used to quantify vadose zone transport of contaminants. The deficiencies have raised questions about the ability of DOE to properly manage waste (GAO 1998). In response to the identification of vadose zone deficiencies, DOE has launched the development of a complex-wide vadose zone roadmap. Because of its leadership in vadose zone research and development, the INEEL is the lead DOE laboratory for the DOE complex-wide vadose zone roadmap. This document provides the basis for science plan development that will be used to create the INEEL Site-wide vadose zone roadmap.

Roadmapping is a process for strategic technology planning. It is used to develop a common perspective on possible future technology needs, systematically evaluate research options and directions, and focus research and development activities. The multidisciplinary process requires the involvement of individuals possessing essential knowledge about an industry or technology. The process systematically identifies critical system requirements, necessary technology, and associated timelines.

1.1 Purpose

This document identifies the deficiencies in the current understanding of vadose zone flow and transport processes at the INEEL and provides recommendations to address the deficiencies. The deficiencies and recommendations were identified and compiled by INEEL scientists and program managers in the fall of 1999. Later, at the Vadose Zone Workshop on October 21 and 22, 1999, in Idaho Falls, Idaho, along with INEEL personnel, non-INEEL cognizant professionals zone reviewed the deficiencies and recommendations, regrouped them, ranked them, and developed outlines to address them. A map of the INEEL and its facilities is provided in Figure 1-1.

The identification of the deficiencies was based on review at the INEEL of several decades of scientific investigations, monitoring, laboratory analyses, field investigations, and remediation of contaminated sites at the INEEL. These investigations led to the development of several conceptual models that attempt to explain contaminant transport in the INEEL vadose zone. These conceptual models are used to advance the level of understanding of the geologic framework, hydrologic processes,

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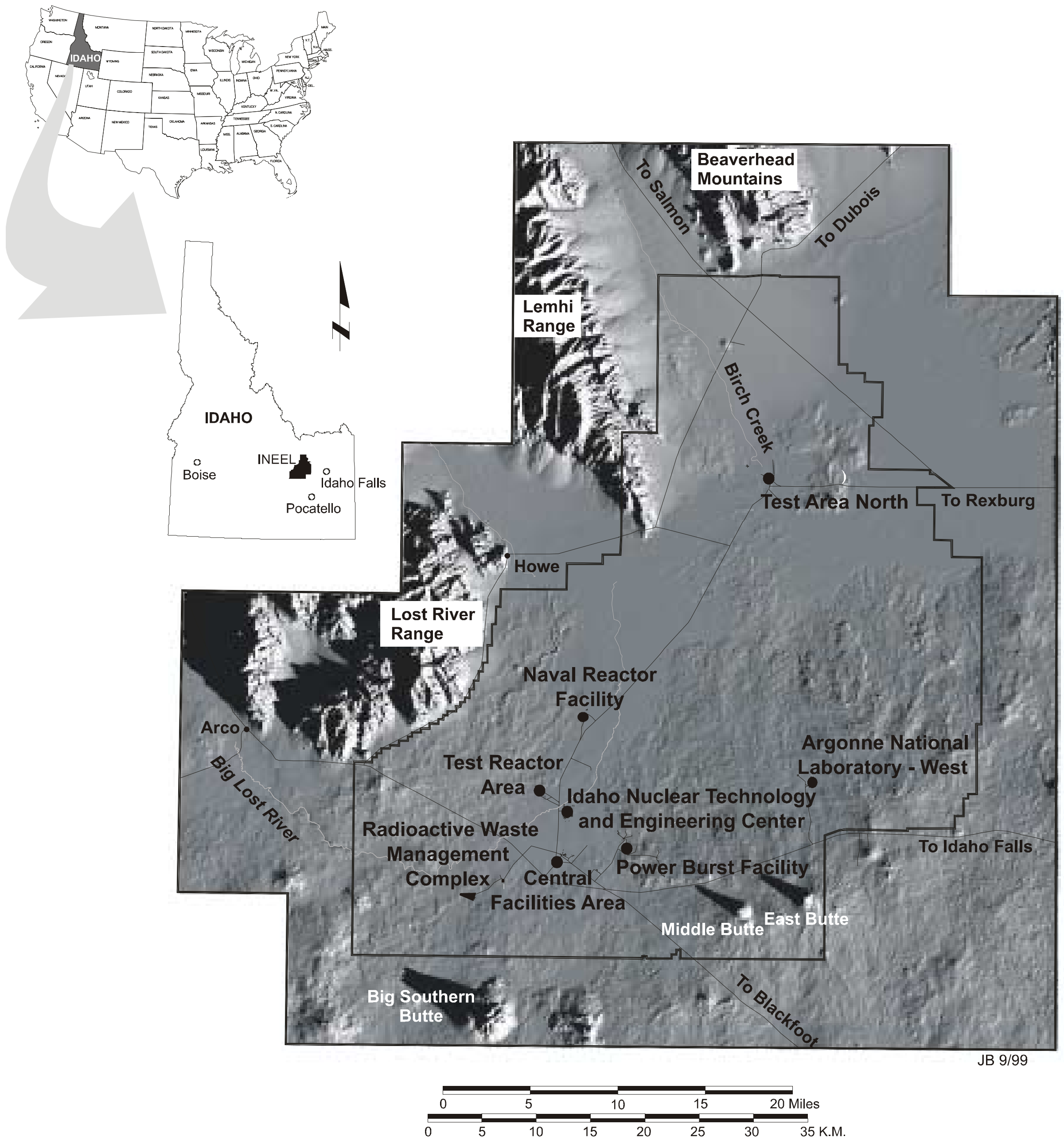

Figure 1-1. Locations of facilities at the Idaho National Engineering and Environmental Laboratory.

contaminant transport, chemical and biological processes affecting transport, and vadose zone contaminant source terms at the INEEL.

At the Vadose Zone Workshop, the deficiencies and recommendations identified by INEEL scientists and project managers were assessed, grouped into seven categories, and ranked. (The initial deficiencies identified by INEEL scientists and project managers were contained in Section 3 of the draft version [Revision 1] of this document and are now provided in Appendix D. The revised deficiencies, after grouping and ranking at the workshop, are presented in Section 3 of this document, the final version of the Vadose Deficiencies document.) Priorities for the recommendations were established based on programmatic risk and technical need. From the findings at the workshop, five science plans are being developed through a series of technical sessions based on the deficiencies and recommendations in this document. The areas of focus of the five science plans include (1) spatial variability, (2) characterization and monitoring, (3) flow and transport modeling and physics of flow, (4) source term, and (5) geochemistry and microbiology. The objective of the plans is to enhance INEEL understanding of vadose zone contaminant flow and transport to advance the ability of the INEEL to conduct environmental assessments and the resulting remediation. The results of the INEEL Workshop will be documented and serve as the basis for the INEEL Site-wide vadose zone roadmapping effort.

1.2 Document Organization

The three major components of this document are described below:

- Section 2—Information is provided about vadose zone investigations that have been conducted at the INEEL.

- Section 3—The deficiencies in understanding of flow and transport mechanisms in the vadose zone at the INEEL are identified and grouped by subject area and recommendations are provided to address the deficiencies. These deficiencies and recommendations reflect the assessment and ranking conducted at the 1999 Vadose Zone Workshop in Idaho Falls, Idaho, of the deficiencies previously identified by INEEL scientists and program managers.

- Appendices—Supporting information about the vadose zone is provided. Vadose zone test site studies and investigations conducted at INEEL facilities are discussed in Appendices A and B, respectively. The conceptual models that have resulted from INEEL vadose zone investigations are discussed in Appendix C. Section 3 of the draft Vadose Zone Deficiencies document (Revision 1), which contains the deficiencies and recommendations previously identified by INEEL scientists and program managers, is provided in Appendix D. A list of the attendees at the 1999 Vadose Zone Workshop is presented in Appendix E.

1.3 Reference

GAO, March 1998, *Nuclear Waste, Understanding of Waste Migration at Hanford Is Inadequate for Key Decisions, Report to Congressional Requestors*, GAO/RCED-98-80, U.S. General Accounting Office, Washington, D.C.

2. INEEL VADOSE ZONE ACTIVITIES

The long history of grappling with and modeling the perplexing vadose zone processes at the INEEL provides a unique viewpoint and competency from which to summarize the deficiencies and recommendations for better scientific understanding of this important zone. It is important that INEEL scientists and program managers proactively address these limitations and needs so that the factors that influence the transport of contaminants can be better known and optimal remediation techniques can be developed for various problem sites.

The interest of the INEEL in deep vadose zone processes is longstanding because of its location on the Eastern Snake River Plain. The plain is a cold, high desert receiving only about 10 in. of precipitation annually, while the depth at the INEEL to the underlying Snake River Plain Aquifer is located roughly from 200 to 900 ft bgs (Becker et al. 1998; Irving 1993). About 9% of the aquifer lies beneath the INEEL (DOE-ID 1996).

Facilities at the INEEL have produced quantities of industrial and radioactive waste that has been disposed of by various processes. The combination of a deep water table, low precipitation, and shallow surficial sediments overlying fractured basalt provides the rationale to perform vadose zone monitoring. Because vadose zone monitoring was instigated by agricultural researchers for sediments at shallow depths, modification of these techniques has been necessary to characterize, monitor, and understand moisture-contaminant movement in deep sediment and fractured rock material applicable to waste disposal facilities.

A summary of vadose zone investigations conducted at the INEEL is provided in Table 2-1. The growth of knowledge about the vadose zone at the INEEL is chronicled in the table.

Table 2-1. INEEL vadose zone investigations.

Dates	Project	Description
Vadose Zone Investigations Performed at the Radioactive Waste Management Complex		
1960–69	Atomic Energy Commission Subsurface Disposal Area (SDA) surficial sediment investigation	This Atomic Energy Commission study focused on installing wells in the surficial sediments in the SDA to obtain water samples. Perched water was found to exist for several years. Strontium-90 and Cs-137 were detected in some of the water samples. Schmalz, B.L., 1972, *Radionuclide Distribution in Soil Mantle of the Lithosphere as a Consequence of Waste Disposal at the National Reactor Testing Station*, IDO-10049, U.S. Atomic Energy Commission, Idaho Operations Office, Idaho Falls, Idaho.
1971–72	U.S. Geological Survey (USGS) SDA vadose zone investigation	The USGS study of the SDA vadose zone had three objectives: (1) to evaluate the geologic, hydrologic, and geochemical variables that could affect the subsurface migration of waste radionuclides; (2) to determine the extent of radionuclide migration, if any; and (3) to construct a groundwater monitoring network. The primary results of this study were the establishment of the lithologic framework in the subsurface and the detection of trace amounts of radionuclides in the interbeds at 110 ft (i.e., the B-C interbed) and 240 ft (i.e., the C-D interbed). A primary conclusion was that migration of contaminants had occurred to the 110-ft interbed, though the possibility of cross contamination was mentioned. Barraclough, J. T., B. Robertson, and V. J. Janzer, August 1976, *Hydrology of the Solid Waste Burial Ground as Related to the Potential Migration of Radionuclides at the Idaho National Engineering Laboratory*, Open File Report 76-471, IDO-22056, U.S. Geological Survey.
1975	Energy Research and Development Administration (ERDA) SDA vadose zone investigation	An investigation was conducted for ERDA in 1975 to confirm the results of the 1971–72 study. This second study focused solely on obtaining samples of the interbeds near two wells that showed contamination in the previous study. From stratigraphic information obtained from this study, a shallow interbed was identified at a depth of 30 ft. During this study, techniques were developed to prevent cross contamination of cores by surface soils, airborne radionuclides, or well-bore contamination. Core samples from the three sedimentary interbeds were analyzed for Cs-137, Ce-144, Pu-238, Pu-239/240, Co-60, Am-241, and Sr-90. The analysis showed no statistically positive radioactivity from waste radionuclides. A conclusion of the study was that sample contamination may have been an important factor in portions of the 1971–72 study because of the absence of waste radionuclides in samples analyzed from this study. Burgus, W. H., and S. E. Maestas, 1976, *The 1975 RWMC Core Drilling Program*, U.S. Energy Research and Development Administration Office, Office of Waste Management, Idaho Operations Office publication, IDO-10065, Idaho Falls, Idaho.

Table 2-1. (continued).

Dates	Project	Description
1976–77	EG&G Idaho SDA vadose zone investigation	A study was conducted during 1976 and 1977 by EG&G Idaho. Two objectives were identified for this study: (1) to sample the sedimentary interbeds in the vadose zone for radiochemical analysis and (2) to analyze samples from the undisturbed soil zone immediately underlying buried waste but above the first basalt. Trace levels of radioactive contaminants were found in interbed soils but were not detected in duplicate analyses. Samples from immediately beneath the waste showed very limited migration with a "halo" of adsorbed transuranic elements. Humphrey, Thomas G., and Fred H. Tingey, October 1978, *The Subsurface Migration of Radionuclides at the Radioactive Waste Management Complex 1976–1977*, TREE-1171, EG&G Idaho, Inc., Idaho Falls, Idaho.
1978	EG&G Idaho SDA vadose zone investigation	A study was conducted in 1978. Its objective was to repeat the 1976–77 study looking for evidence of radionuclide migration. A complete set of new samples was obtained from core material collected in the 1976 and 1977 core drilling programs. This investigation indicated that there was no conclusive evidence that radionuclides originating from the buried waste had migrated to the underlying Snake River Plain Aquifer. The study concluded that most positive results observed in core samples from all studies since 1975 were probably a result of statistical variation rather than evidence of radionuclide migration. Humphrey, T. G., 1980, *Subsurface Migration of Radionuclides at the Radioactive Waste Management Complex 1978*, EGG-2026, EG&G Idaho, Inc., Idaho Falls, Idaho.
1979	EG&G Idaho SDA vadose zone investigation	Three additional wells were drilled in and around the Radioactive Waste Management Complex (RWMC) to collect core samples of interbeds for radionuclide analysis. Radioactive contamination was detected in the interbed at 110 ft (i.e., the B-C interbed). Bargelt, R. J., C. A. Dicke, J. M. Hubbell, M. Paarmann, D. Ryan, R. W. Smith, and T. R. Wood, January 1992, *Summary of RWMC Investigations Report*, EGG-WM-9708, EG&G Idaho, Inc., Idaho Falls, Idaho.

Table 2-1. (continued).

Dates	Project	Description
1983–90	SDA Subsurface Investigations Program	The Subsurface Investigations Program (SIP) was a multidisciplinary collaborative program between EG&G Idaho and the U.S. Geological Survey (USGS). The SIP was conducted at the SDA to achieve two major objectives: (1) to collect sufficient vadose zone field data to calibrate a model of long-term radionuclide migration and (2) to determine the extent of radionuclide migration. Clean-drilling techniques were developed to prevent downhole contamination when drilling through contaminated surficial sediments. Numerous deep and shallow boreholes were drilled at the RWMC to collect sample material for evaluation of radionuclide content in the interbeds, to determine geologic and hydrologic characteristics of the sediments, and to provide monitoring sites for moisture movement in these sediments. Suction lysimeters and heat dissipation sensors were installed in deep boreholes to collect moisture data. Moisture sensing instruments (tensiometers, thermocouple psychrometers, gypsum blocks, heat dissipation sensors, and neutron loggers) were installed in shallow sediments and monitored. Because of the large volume of collected data, the RWMC Data Management System was developed and implemented to facilitate the storage, retrieval, and manipulation of the database. Sampling of ambient air, air in boreholes, and soil gases was conducted at the RWMC to determine the identity, location, and relative concentrations of selected chlorinated and aromatic volatile organic compounds (VOCs). Measurable concentrations of VOCs were detected in soil gases at distances from 2,000 to 3,400 ft from the SDA boundary. Analyses of gases collected at various depths beneath the RWMC indicated maximum gas concentrations at around 100 ft below land surface, and measurable concentrations to 576 ft. Sampling of radionuclides in cores recovered from the interbeds conclusively demonstrated migration of actinides to the interbed at 110 ft (i.e., the B-C interbed) in at least one location in the SDA. Migration to the interbed at 240 ft (i.e., the C-D interbed) at this same location was possible but was not confirmed at the same level. Laney, P. T., S. C. Minkin, R. G. Baca, D. L. McElroy, J. M. Hubbell, L. C. Hull, B. F. Russell, G. J. Stormberg, and J. T. Pittman, April 1988, *Annual Progress Report: FY-1987: Subsurface Investigations Program at the Radioactive Waste Management Complex of the Idaho National Engineering Laboratory*, DOE/ID-10183, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho. 1995 to 1998 annual SIP reports
1985–present	USGS Test Trench	Ambient precipitation into undisturbed and disturbed soils is monitored. In addition, infiltration and moisture redistribution under ponding conditions also are monitored.

Table 2-1. (continued).

Dates	Project	Description
1988	Hydraulic properties of surficial sediment	An investigation of the hydraulic properties of surficial sediment was conducted by J. V. Borghese for a thesis study at the University of Idaho. Borghese reported on hydraulic characteristics including saturated hydraulic conductivity, grain size, bulk density, and porosity of surficial soils. Borghese, J. V., 1988, *Hydraulic Characteristics of Soil Cover, Subsurface Disposal Area, Idaho National Engineering Laboratory*. M.S. Thesis, University of Idaho, Moscow, Idaho.
1991	Hydraulic properties of surficial sediments	An investigation of in situ characterization of unsaturated hydraulic properties of surficial sediments was conducted by J. F. Kaminsky for a thesis study at Idaho State University. The investigation used a field plot that was flooded, covered, and allowed to drain. Kaminsky, J. F., 1991, *In Situ Characterization of Unsaturated Hydraulic Properties of Surficial Sediments Adjacent to the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho*. M.S. Thesis, Idaho State University, Pocatello, Idaho.
1991	Hydraulic properties of vesicular basalt	An investigation of hydraulic properties of a block of RWMC vesicular basalt was conducted by C. W. Bishop for a thesis study at the University of Arizona. Saturated and unsaturated hydraulic properties, moisture characteristic curves, and infiltration rates were measured. Bishop, C. W., 1991, *Hydraulic Properties of Vesicular Basalt*. M.S. Thesis, University of Arizona, Tucson, Arizona.
1988–92	RWMC basalt characterization	An investigation was conducted of the geology, lithology, stratigraphy, and hydrology of basalt flows, sedimentary interbeds, and fractures in the basalts. Knutson, C. F., K. A. McCormick, R. P. Smith, W. R. Hackett, J. P. O'Brien, and J. C. Crocker, 1989, *FY 89 Report RWMC Vadose Zone Basalt Characterization*, EG&G Idaho, Inc., Idaho Falls, Idaho.
1992–ongoing	Cold test investigations	Treatability studies including in situ grouting and in situ vitrification were conducted at a cold mock-up waste site. Geophysical methods to characterize cold waste have been developed. Loomis, G. G., A. P. Zdinak, and C. W. Bishop, 1996, *Innovative Subsurface Stabilization Project—Final Report*, INEEL-96/0439, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.

Table 2-1. (continued).

Dates	Project	Description
1992–present	Organic Contamination in the Vadose Zone	A large, diffuse volatile organic plume emanating from the SDA has been under CERCLA investigation since 1992. Organic contamination was first discovered in exhaling well in 1987. Vadose zone monitoring network consisting of monitoring wells with gas ports and extraction wells. A series of feasibility and treatability tests preceded development of a full-scale remediation system. Duncan, F. L., and R. E. Troutman, Dames & Moore, and J. A. Sondrup, EG&G Idaho, Inc., December 1993, *Remedial Investigation/Feasibility Study Report for the Organic Contamination in the Vadose Zone—Operable Unit 7-08*, EGG-ER-10684, EG&G Idaho, Inc., Idaho Falls, Idaho. Bechtel BWXT Idaho, LLC, November 1999, *Interim Phase II Remedial Action Report for Organic Contamination in the Vadose Zone Operable Unit 7-08*, INEEL/EXT-99-00742, Revision 0, Idaho Falls, Idaho.
1993–96	SDA perched water and moisture monitoring	Monitoring of moisture contents and matric potentials in the surficial sediments and perched water levels in association with the interbeds resumed. In 1994, the monitoring network was expanded from two locations to 23 locations. One-dimensional inverse modeling was performed to calibrate a model at each monitoring location. Annual infiltration calculated directly from the moisture monitoring and from the inverse modeling was estimated to range from less than 1 cm/year to greater than 30 cm/year depending on the topography, history of soil freezing, and degree of disturbance of the soil profile. Hubbell, J. M., et al., 1985, *Annual Progress Report*, DOE/ID-10136, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho. McElroy, D. L., 1993, *Soil Moisture Monitoring Results at the RWMC of the INEL*, EGG-WM-11066, EG&G Idaho, Inc., Idaho Falls, Idaho. Hubbell, J. M., November 1993, *Perched Groundwater Monitoring in the Subsurface Disposal Area of the Radioactive Waste Management Complex*, Engineering Design File EDF ER&WM-EDF-002293, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho. Bishop, C. W., 1998, *Soil Monitoring Results at the RWMC of the INEL, FY-96, FY-95, and FY-94*, INEEL 98-00941, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho. Martian, P., and S. M. Magnuson, 1995, *A Simulation Study of Infiltration into Surficial Sediments at the SDA, INEL*, EGG-WM-112250, EG&G Idaho, Inc., Idaho Falls, Idaho.
1993	Analysis of interbed sediments	An investigation of the characteristics of sedimentary interbeds at the RWMC was conducted by J. Hughes for a thesis study at Idaho State University. J. Hughes, 1993, *Analysis of Characteristics of Sedimentary Interbeds at the RWMC, INEL, Idaho*. MS Thesis, Idaho State University, Pocatello, Idaho.

Table 2-1. (continued).

Dates	Project	Description
1993–98	Passive venting studies and Barometrically Enhanced Remediation Test	Concurrent with the Organic Contamination in the Vadose Zone (OCVZ) active remediation, a series of studies were conducted that investigated the feasibility of using wells with one-way valves at the surface that used barometric pressure fluctuations to vent volatile organics in the subsurface to the atmosphere.
1993–94	Large-Scale Infiltration Test	An innovative field-scale investigation was conducted of water and radioactive tracer movement under variably saturated conditions down through fractured basalt. Transport of conservative and reactive tracers was monitored through fractures and in perched water on interbed. Interaction with sedimentary interbed caused perched water to develop and lateral spreading to occur. The infiltration basin was 600 ft in diameter and the investigation depth to a dominant sedimentary interbed was 180 ft. The study showed preferential flow locally but predominantly vertical movement defined by a cylinder projecting downwards from the basin. Vadose zone monitoring instruments, gamma spectrometer logging, and geophysical resistivity techniques were used to investigate the movement of water and tracers. Wood, T. R., and G. T. Norrell, 1996, *Integrated Large-Scale Aquifer Pumping and Infiltration Tests, Groundwater Pathways OU 7-06, summary Report*, INEL-96/10256, Rev. 0, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho. Wylie, A. H., J. M. McCarthy, E. Neher, and B. D. Higgs, February 22, 1995, *Large-Scale Aquifer Pumping Test Results*, Engineering Design File WAG7-56, INEL-95/012, EG&G Idaho, Inc., Idaho Falls, Idaho.
1994	Physical properties of sediments	An investigation of the physical properties of sediments affecting saturated vertical flow was conducted by W. Pudney for a thesis study at Idaho State University. Pudney, W., 1994, M.S. Thesis, Idaho State University, Pocatello, Idaho.
1995–ongoing	Engineered Barrier Test	The purpose of the investigation is to examine the effectiveness of native soil covers under natural and enhanced precipitation regimes. The effectiveness of vegetation also will be studied. Porro, I, and K. N. Keck, 1998, *Engineered Barrier Testing at the INEEL Engineered Barriers Test Facility: FY-1997 and FY-1998*, INEEL/EXT-98-00964, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.
1995–ongoing	Tritium and C-14 monitoring	Soil gas has been monitored for tritium and ^{14}C near a beryllium reactor block burial site to determine releases from the beryllium and transport pathways. Moisture monitoring and soil water sampling also are conducted at the burial site. Ritter, P. D., and D. L. McElroy, 1999, *Progress Report Tritium and Carbon-14 Sampling at the RWMC*, INEEL/EXT-98-00669.

Table 2-1. (continued).

Dates	Project	Description
1995	Hydraulic properties, disturbed sediment	An investigation comparing hydraulic properties determined for undisturbed soil and soil used to cover a simulated waste filled trench was conducted by S. Shakofsky for a thesis study. Shakofsky, S., 1995, *Changes in Soil Hydraulic Properties Caused by Construction of a Simulated Waste Trench at the INEL*, Idaho, DOE-ID-22121, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.
1996	Bomb Tracer Investigation	Surficial sediment cores were collected from the SDA in an area where surface ponding develops to look for bomb pulse tracers. Point of contact: D. L. Cecil, U.S. Geological Survey, Idaho Falls, Idaho.
1997	Magnesium chloride determination	Soil samples were collected from shallow holes drilled in the surficial sediments for analysis of magnesium chloride. A magnesium chloride brine was applied to SDA roads as a dust suppressant. Sample holes were instrumented with suction lysimeters. Point of contact: C. W. Bishop, INEEL.
1997–ongoing	Long-Term Corrosion Test	Corrosion coupons for a variety of metals are buried at 4- and 10-ft depths in a soil berm constructed of Spreading Area B soils. Coupons were recovered following 1 year of burial. Subsequent retrievals will be defined in a revised test plan. Metals tested are carbon steel, stainless steel, aluminum, Inconel, Zircaloy-4, beryllium, and ferralium. Mizia, R. E., et al., 1999, "The Long Term Corrosion/Degradation Test One Year Results," INEEL/EXT-99-00678, Draft, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.
1997–ongoing	Active waste monitoring	Monitoring instrumentation (lysimeters, tensiometers, and gas ports) was installed below and between waste boxes stacked in the Active Waste Monitoring Pit. Instrumentation will continue to be installed as the pit is filled. The instrumentation will be used to monitor moisture movement into and beneath the waste disposal area. C. W. Bishop, 1997, *Monitoring System Plan for the Low-level Waste Disposal Pit at the RWMC,* INEL/INT-97/00012, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.
1997	Acid Pit grouting	Demonstration of an in situ grouting of waste at the RWMC Acid Pit. Point of contact: G. G. Loomis, INEEL.
1996–ongoing	WAG 7 sampling and perched water monitoring	Quarterly soil water samples are collected from suction lysimeters installed in surficial sediments, basalt, and interbeds for contaminant analyses. Perched water levels are monitored. Becker, B. H., J. D. Burgess, K. J. Holdren, D. K. Jorgensen, S. O. Magnuson, and A. J. Sondrup, August 1998, *Interim Risk Assessment and Contaminant Screening for the Waste Area Group 7 Remedial Investigation*, DOE/ID-10569, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.

Table 2-1. (continued).

Dates	Project	Description
Slated to start in 2000	WAG 7 characterization studies	Moisture monitoring instrumentation will be installed in probeholes to collect leachate within and beneath waste and to determine infiltration rates occurring through the waste pits in the SDA. A data quality objective plan is being developed and will be implemented to identify further characterization of the SDA. Bechtel BWXT Idaho, LLC, July 2000, "Revised Scope of Work for the OU 3-14 Waste Area Group 7 Comprehensive Remedial Investigation/Feasibility Study," INEL/95-0253, Draft Revision 2, Idaho Falls, Idaho.
1996–ongoing	WAG 7 Work Plan Addendum	Actinide migration mechanisms: observations of plutonium and americium in selected locations deep within the subsurface at the SDA have resulted in the hypothesis that facilitated transport has occurred at the SDA. A study is under way to identify mechanisms that contribute to facilitated transport at the SDA. The study consists of laboratory column tests in which various controlling parameters are sequentially modified. U.S. Department of Energy, Idaho Operations Office, August 1998, *Addendum to the Work Plan for the Operable Unit 7-13/14 Waste Area Group 7, Comprehensive Remedial Investigation/Feasibility Study*, DOE/ID-10622, Idaho Falls, Idaho.
Ongoing	WAG 7 SDA colloidal sampling	Samples from the vadose zone perched water and lysimeter monitoring network and from SDA vicinity aquifer wells were collected to evaluate colloidal concentrations in soil water and identify the concentrations of plutonium and uranium isotopes associated with the colloids. This collaborative effort between the INEEL and Los Alamos National Laboratory is under way. Roback, Robert C., Deward W. Efurd, Michael T. Murrell, and Robert E. Steiner, Los Alamos National Laboratory, July 20, 2000, "Assessment of U and Pu in the Saturated and Unsaturated Zones Beneath the Surface Disposal Area, INEEL," Draft, Los Alamos National Laboratory.
Vadose Zone Investigations Performed at the Central Facilities Area		
1988–91	RCRA CFA monitoring project	A shallow drilling program was implemented at the Central Facilities Area (CFA) Landfill II and III. The objectives that were identified for this study included (1) to define the geologic and hydrologic characteristics of the shallow surficial sediments at the landfills, (2) to quantify the amounts and rates of water movement into and through the sediments, and (3) to sample the sediments and soil gas for contaminants. To accomplish these goals, shallow boreholes were augered adjacent to the backfilled pit and trenches. The boreholes were instrumented with moisture-and contaminant-sensing probes and access ports. Data from January through September 1988 indicated no significant water movement through the sediments below approximately 6 ft. Chemical analyses of soil samples indicated positive responses for acetone and methylene chloride. Gas sampling at the landfills found methylene chloride, benzene, total hydrocarbons, and methane.
1990	Soil Cover Characterization	An investigation to characterize the soil cover and estimate water infiltration at CFA Landfill II was conducted by L. F. Hall for a thesis study at the University of Idaho. Hall, I. F., 1990, *Characterization of Soil Cover and Estimation of Water Infiltration at Central Facilities Area Landfill II, INEL*. M.S. Thesis, University of Idaho, Moscow. Idaho.

Table 2-1. (continued).

Dates	Project	Description
1993	RI/FS CFA Monitoring project	Neutron probe moisture monitoring, heat dissipation sensor monitoring, and salinity sensor monitoring were conducted at CFA Landfill II and III. Deep drainage estimates were from 1 to 15 in. and appeared to be related to snowmelt and subsequent ponding rather than total precipitation. Keck, K. N., I Porro, A. J. Sondrup, S. H. McCormick, and S. M. Lewis, February 1995, *Remedial Investigation/Feasibility Study for Operable Unit 4-12: Central Facilities Area Landfills I, II, and II at the Idaho National Engineering Laboratory*, Vol. I, “Remedial Investigation,” INEL-94/0124, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.
1996–98	RI/FS Record of Decision compliance monitoring of landfill cover	Compliance monitoring under the Record of Decision for CFA Landfill I, II, and III was required to establish the performance of the cover design with respect to infiltration. This monitoring program incorporated neutron probe monitoring and time-domain reflectometry array logging to evaluate infiltration through and in the landfill covers. The vadose zone monitoring program also incorporated soil gas monitoring for tracking any changes in contaminant migration from the landfills. Lockheed Martin Idaho Technologies Company, 1999, “Post-Record of Decision Monitoring Report at Operable Unit 4-12, Central Facilities Area Landfill I, II, and III (Draft),” INEEL/EXT-99-00353, Idaho Falls, Idaho.
Vadose Zone Investigations Performed at the Test Reactor Area		
1960–77	USGS Vadose Zone Investigation	A shallow perched water zone underlying warm waste ponds was studied: 25 shallow holes were augered to trace and monitor waste movement under the ponds. The rate of infiltration from ponds was approximately 7 to 10 g/ft^2/day, and the rate through the sides of the ponds was estimated at 35 to 50 g/ft^2/day. A dye tracer test indicated a velocity of 5 ft/hour in alluvium near the pond. Samples also were collected for physical property analyses. The movement of water in the unsaturated zone beneath the Test Reactor Area (TRA) Warm Waste Pond was studied. Surficial sediment samples were analyzed for hydrologic properties. In 1968, an additional 22 auger holes were drilled around the warm waste pond and sampled for Cs-137, Sr-90, Co-60, and Ce-144. Seven wells were drilled around the retention basin inside the TRA facility in 1967. Schmalz, B. L., October 1972, *Radionuclide Distribution in Soil Mantle of the Lithosphere as a Consequence of Waste Disposal at the National Reactor Testing Station*, IDO-10049, Atomic Energy Commission, Idaho Operations Office, Idaho Falls, Idaho. Robertson, J. B., 1977, *Numerical Modeling of Subsurface Radioactive Solute Transport from Waste-Seepage Ponds at the Idaho National Engineering Laboratory,* Open-File Report 76-717, IDO-22057, U.S. Geological Survey, Idaho Falls, Idaho.

Table 2-1. (continued).

Dates	Project	Description
1989–91	EG&G Investigation	Existing data were analyzed and a conceptual model was developed to describe the movement of water and contaminants associated with the TRA Warm Waste Ponds. Surficial and interbed sediments were collected and analyzed for physical and hydrological properties in 1990 and 1991. Additional shallow alluvial and deeper perched water wells were augered or drilled as a part of this investigation. Two coreholes were cored to obtain detailed lithologic information on the subsurface at the TRA. These wells were installed to address data gaps identified in the conceptual model. Borehole slug tests were performed to determine field-scale hydraulic conductivity values for suspected perching layers associated with the deep perched water zone at the TRA. Field-scale horizontal hydraulic conductivities ranged from 5.18E-03 to 17.3 ft/day, generally higher than the hydraulic conductivities determined by laboratory analyses of interbed cores (3.60E-06 to 3.97 ft/day). Doornbos, M. H., J. L. Mattick, D. L. McElroy, L. V. Street, C. S. Blackmore, and C. A. Dicke, 1991, *Environmental Characterization Report for the Test Reactor Area* (Rev. 0), EGG-WM-9690, EG&G Idaho, Inc., Idaho Falls, Idaho. Hull, L. C., 1989, *Conceptual Model and Description of the Affected Environment for the TRA Warm Waste Pond (Waste Management Unit TRA-03),* Informal Report EGG-ER-8644, EG&G Idaho, Inc., Idaho Falls, Idaho.
1991	Perched Water Aquifer Test	Perched water under the Warm Waste Ponds was tested to determine saturated hydraulic conductivity and transmissivity. Bishop, C. W., A. H. Wylie, and J. L. Mattick, 1992, *Results of Perched Water Aquifer Testing at TRA*, EGG-WM-10014, EG&G Idaho, Inc., Idaho Falls, Idaho.
Vadose Zone Investigations Performed at the Idaho Nuclear Technology and Engineering Center		
1959	Deep perched water well installed	Well USGS-50 was installed in deep perched water (405 ft). The USGS conducts quarterly sampling. Robertson, J. B., R. Schoen, and J. T. Barraclough, 1974, *The Influence of Liquid Waste Disposal on the Geochemistry of Water at the National Reactor Testing Station, 1952—1970*, U.S. Geological Survey Open File Report, IDO-22053, TID-4500, Atomic Energy Commission, Idaho Field Office, Idaho Falls, Idaho.
1981–94	Tank Farm and Vadose Zone Investigations	Shallow holes (~ 45 ft) were installed to measure radioactivity, soil moisture, and perched water. The site investigation was conducted by Golder Associates. Golder Associates, 1994, “1994 Tank Farm Drilling and Sampling Investigation at the ICPP (Draft).”

Table 2-1. (continued).

Dates	Project	Description
1986	Shallow perched water wells installed around percolation ponds	Shallow perched water wells were installed and monitored quarterly for 1 year under a RCRA compliance program. Rodriguez, R. R., A. L. Schafer, J. McCarthy, P. Martian, D. E. Burns, D. E. Raunig, N. A. Burch, and R. L. VanHorn, November 1997, *Comprehensive RI/FS for the Idaho Chemical Processing Plant OU 3-13 at the INEEL—Part A, RI/BRA Report (Final)*, DOE/ID-10534, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.
1992	Suction lysimeter installation	Suction lysimeters were installed at the Tank Farm but were not sampled.
1992	Perched Water Slug Tests	Shallow perched water wells at the Idaho Nuclear Technology and Engineering Center (INTEC) were slug tested to determine hydraulic conductivity and transmissivity.
1995	Correlation of Basalt Flows	An investigation correlating the stratigraphy and characteristics of basalt flows beneath the INTEC, formerly the Idaho Chemical Processing Plant (ICPP), was conducted by M. F. Reed for a thesis study at Idaho State University. Reed, M. F., 1995, *Stratigraphic Correlations and Characterization of Basalt Flows Beneath the ICPP, INEL, Idaho*. M.S. Thesis, Idaho State University, Pocatello, Idaho.
1995	Perched Water Sampling	Comprehensive perched water sampling and contaminant analyses were conducted by Waste Area Group 3-13.
Ongoing	Tank Farm Soil and Groundwater Remedial Investigation/Feasibility Study	Operable Unit 3-14 will investigate infiltration. Shallow (~ 45-ft) holes will be drilled and instrumentation will be installed. Soil and water samples will be collected to provide information for contaminant trend analyses. U.S. Department of Energy, Idaho Operations Office, July 2000, "Draft Operable Unit 3-14, Tank Farm Soil and Groundwater Remedial Investigation/Feasibility Study," DOE/ID-10676, Idaho Falls, Idaho.
Ongoing	Tank Farm Interim Actions	Operable Unit 3-13 will investigate means to limit infiltration at the Tank Farm. U.S. Department of Energy, Idaho Operations Office; U.S. Environmental Protection Agency, Region 10; Idaho Department of Health and Welfare, Division of Environmental Quality, October 1999, *Final Record of Decision, Idaho Nuclear Technology and Engineering Center, Operable Unit 3-13, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho*, DOE/ID-10660, Rev. 0.
Vadose Zone Investigations Performed at the Test Area North		
—	—	No investigations have been conducted.

Table 2-1. (continued).

Dates	Project	Description
Vadose Zone Investigations Performed Outside of Facility Boundaries		
1952–70	Early USGS Geology and hydrology investigations	Several studies have been performed. Deutsch, M., P. T. Vogal, R. L. Nace, and J. R. Jones, 1952, *Geology and Ground Water in the North Eastern Part of the National Reactor Testing Station, Idaho*, U.S. Geological Survey, Idaho Falls, Idaho.
1978–95	Soil mapping studies	A variety of mapping studies were conducted to characterize surface soils and vegetation.
1990	Mineralogy and petrology study	An investigation on the mineralogy, petrology, and grain size of surficial sediments from the Big Lost River, Little Lost River, and Birch Creek drainages was conducted by R. C. Bartholomay for a thesis study at Idaho State University. Bartholomay, R. C., 1990, *Mineralogy, Petrology, and Grain Size of Surficial Sediments from the Big Lost River, Little Lost River and Birch Creek Drainages*, M.S. Thesis, Idaho State University, Pocatello, Idaho.
1990–96	Basalt flow correlation	U.S. Geological Survey studies were performed that correlated basalt stratigraphy using well logs. Anderson, S. R., and M. J. Liszewski, 1996, *Stratigraphic Data for Wells over the INEL, Idaho*, Open File Report 96-248; U.S. Geological Survey. Anderson, S. R., 1991, *Stratigraphy of the Unsaturated Zone And Uppermost Part of the Snake River Plain Aquifer at the Idaho Chemical Processing Plant and Test Reactor Area, Idaho National Engineering Laboratory, Idaho*, Water Resources Investigation Report 91-4010, DOE/ID-22095, U.S. Geological Survey, Idaho Falls, Idaho. Anderson, S. R., and B. D. Lewis, 1989, Stratigraphy of the Unsaturated Zone at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho, Water Resources Investigations Report 89-4065, IDO-22080, U.S. Geological Survey, Idaho Falls, Idaho. Bartholomay, R. C., 1990, *Mineralogical Correlation of Surficial Sediment from Area Drainage with Selected Sedimentary Interbeds at the Idaho National Engineering Laboratory, Idaho*, U.S. Geological Survey Water-Resources Investigations Report 90-4147, DOE/ID-22092, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.
1991–94	Geostatistical study of basalt	Geostatistical study of basalt flow morphology. Basalt flows were located at Hell's Half Acre and Box Canyon sites. Knutson, C. F., K. A. McCormick, R. P. Smith, W. R. Hackett, J. P. O'Brien, and J. C. Crocker, 1990, *FY-89 Report RWMC Vadose Zone Basalt Characterization*, EGG-WM-8949, EG&G Idaho, Inc.

Table 2-1. (continued).

Dates	Project	Description
1993	Soil cap studies	Idaho State University investigated soil moisture and ways to control infiltration. Anderson, Jay E., Mark L. Shumar, Nancee L. Toft, Idaho State University, and Robert S. Nowak, University of Nevada—Reno, "Control of the Soil Water Balance by Sagebrush and Three Perennial Grasses in a Cold-Desert Environment," *Arid Soil Research and Rehabilitation*, Vol. 1, pp. 229–244. Anderson, Jay E., Robert S. Nowak, Teresa D. Ratzlaff, and O. Doyle Markham, November 1991, *Managing Soil Moisture on Waste Burial Sites*, DOE/ID-12123, U.S. Department of Energy, Idaho Field Office, Radiological and Environmental Science Laboratory, Idaho Falls, Idaho.
1994	Flow path study	Infrared was used to identify fast flow paths at the exposed basaltic cliff face at the Box Canyon site. Knutson, C. F., D. O. Cox, K. J. Dooley, and J. B. Sisson, October 6, 1993, "Characterization of Low-Permeability Media Using Outcrop Measurements," *66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Dallas, Texas*.
1995	Earth Mound Investigation	An investigation characterizing the origin or earth mounds on the Eastern Snake River Plain was conducted by J. A. Tullis for a thesis study at Idaho State University. Tullis, J. A., 1995, *Characteristic and Origin of Earth Mounds on the Eastern Snake River Plain*. M.S. Thesis, Idaho State University, Pocatello, Idaho.
1995–ongoing	Box Canyon Investigation	Intermediate-scale investigation of water movement and monitoring techniques next to a basalt outcrop along the Box Canyon section of the Big Lost River. Knutson, C. F., K. A. McCormick, R. P. Smith, W. R. Hackett, J. P. O'Brien, and J. C. Crocker, 1990, *FY-89 Report RWMC Vadose Zone Basalt Characterization*, EGG-WM-8949, EG&G Idaho, Inc.
1995–ongoing	Vadose Zone instrument development	The development of the Advanced Tensiometer allowed for deep vadose zone monitoring. Development of the tensiometer for monitoring in deep vadose zones will support determining temporal and spatial variability of soil-water potential in the deep vadose zone. Monitoring is being conducted at and data are being evaluated from semiarid sites (INTEC, the RWMC, the INEEL Research Center, and Hanford Buried Waste Tank Farm) and humid sites (Oak Ridge and Savannah River). Vadose zone monitoring and sampling instrumentation development will support field definition and characterization of the deep vadose zone (> 2 m). Hubbell, J. M., and J. B. Sisson, April 1998, "Advanced Tensiometer for Shallow or Deep Soil Water Potential Measurements," *Soil Science*, Vol. 163, No. 4, pp. 271–277.

Table 2-1. (continued).

Dates	Project	Description
1996–ongoing	Hell’s Half Acre	A meter-scale investigation is being conducted of water movement through a single fracture and a small network of fractures in a basalt overhang on the Hell’s Half Acre extrusive basalt flow. Instrumentation is being developed and the hypothesis is being corroborated to show that water movement in the fractures in the basalt can be described using chaos theory. Faybishenko, B. A., 1998, “Theory and Numerical Evaluation of the Parameters of the Chaotic Behavior of Flow in Unsaturated Soils and Rocks,” abstract presented at the Chapman Conference on Fractal Scaling, Nonlinear Dynamics, and Chaos in Hydrologic Systems, Clemson University, Clemson, South Carolina.

2.1 References

Becker, B. H., J. D. Burgess, K. J. Holdren, D. K. Jorgensen, S. O. Magnuson, and A. J. Sondrup, August 1998, *Interim Risk Assessment and Contaminant Screening for the Waste Area Group 7 Remedial Investigation*, DOE/ID-10569, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.

DOE-ID, March 1996, *Idaho National Engineering Laboratory Comprehensive Facility and Land Use Plan*, DOE/ID-10514, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Irving, J. S., July 1993, *Environmental Resource Document for the Idaho National Engineering Laboratory*, EGG-WMO-10279, EG&G Idaho, Inc., Idaho Falls, Idaho.

3. INEEL VADOSE ZONE DEFICIENCIES

Various types of contamination, including radioactive and mixed waste, affect sites throughout the DOE complex. The waste, mostly generated by weapons production and waste management activities, has contaminated millions of cubic meters of subsurface media at 132 sites. Much of the risk associated with long-term remedial activities and stewardship responsibilities at these sites resides in the vadose zone. Because contaminant characterization and accurate fate and transport modeling in these complex hydrogeologic systems can be formidable, increasing the level of understanding of vadose zone processes through better science, characterization, modeling, and correct technology application is critical for effective operation, cleanup, and final disposition of the DOE facilities.

The INEEL Vadose Zone Science and Technology Roadmap is an important step in rationalizing a science program necessary to develop and coordinate long-term interdisciplinary research into the vadose zone processes that affect fluid movement, contaminant transport, and chemical transformation processes. In support of the INEEL vadose zone roadmap, the draft Vadose Zone Deficiencies document titled, "Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory (Draft)," was written in October 1999. The purpose of the document was to provide a process for DOE and INEEL managers and scientist to (1) identify areas where current knowledge of vadose zone processes is deficient and (2) create science plans to address these deficiencies. The draft Vadose Zone document was created by scientists and project managers at the INEEL. The INEEL personnel identified more than 100 specific deficiencies, contained in Section 3 of draft document. (Section 3 of the draft document is now contained in Appendix D of this document.) The draft Vadose Zone Deficiencies document formed the basis for the Vadose Zone Deficiencies Workshop[a] conducted in Idaho Falls, Idaho, on October 20 and 21, 1999, and attended by INEEL and non-INEEL scientists and program managers and cognizant professionals. Based on the consensus reached at the workshop, the final version of the Vadose Zone Deficiencies document was prepared. In Section 3 of this document, the final version of the Vadose Zone Deficiencies document, the deficiencies are validated, regrouped, and ranked by the workshop attendees. Otherwise, the bulk of the remainder of the draft Vadose Zone Deficiencies document is unchanged in the final version of the document.

The INEEL Vadose Zone Deficiencies Workshop was conducted to develop science plans and address deficiencies in understanding of vadose processes that limit reliable predictions of water and contaminant movement in the subsurface. The intent was to present the deficiencies to a broad audience of INEEL contractors and researchers, other national laboratory and university researchers, and project managers for their endorsement and to develop a path forward to fill gaps and to satisfy vadose zone needs for achievement of roadmap development.

The Vadose Zone Deficiencies Workshop was conducted as a precursor to roadmap development. The objectives of the workshop included the following:

- Review, validate, and comment on needs and recommendations identified in the draft Vadose Zone Deficiencies document
- Rank the deficiencies and recommendations
- Capture minority and majority opinions

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a. The attendees at the INEEL Vadose Zone Workshop are listed in Appendix E.

- Draft science-based recommendations and science plans to address deficiencies in vadose zone scientific knowledge.

3.1 Workshop Recommendations

Workshop participants reviewed the draft Vadose Zone Deficiencies document, ranked the identified deficiencies, grouped the deficiencies into seven subject areas, and made preliminary outlines for the science plans to address the deficiencies. The findings of the workshop participants are discussed in the following sections.

The science plan outlines drafted during the workshop serve as a basis on which to develop science plans with a level of detail to be effectively used to address the deficiencies identified at the workshop and for DOE decision-making purposes. Five science plans are being developed from the seven subject areas described below. The focus areas of the five science plans include (1) spatial variability, (2) characterization and monitoring, (3) flow and transport modeling and physics of flow, (4) source term, and (5) geochemistry and microbiology. This grouping was necessary to reduce the number of science plans to a manageable level.

The seven subject areas for science plan guidelines and identified deficiencies are identified below. The deficiencies and associated recommendations described in this section were developed and should be viewed within the context of the conceptual models outlined in Appendix C. The conceptual models that have been developed at the INEEL describe the geologic framework, the hydrologic environment, the transport mechanisms causing contaminant movement, and the geochemical controls on transport mechanisms and represent the state of knowledge of the vadose zone and its geologic and hydrologic context at the INEEL. The models are based on several decades of cumulative experience at the INEEL and on the state of scientific knowledge for each discipline.

Though the deficiencies and recommendations were developed specifically for vadose zone conditions at the INEEL, they are equally applicable to most vadose zone conditions, particularly fractured rock sites in arid and semiarid regions. Review of current literature and scientific interchanges between geoscientists at the INEEL and at other DOE sites indicate that the vadose zone problems faced at the INEEL are universal in nature (e.g., GAO 1998; Rousseau, Kwicklis, and Gillies 1997; Eaton et al. 1996). Throughout the DOE complex, similar problems result from, for example, spatial variability, paucity of data, and uncertainty in flow and transport modeling, to name a few.

Workshop participants consolidated the deficiency list into the seven subject areas, and developed specific needs for each area. Participants did not develop recommendations to address the deficiency areas. The recommendations provided below were identified by INEEL scientists and program managers in the draft Vadose Zone Deficiencies document. The seven subject areas of deficiencies are discussed as follows:

- Section 3.1.1 Spatial Variability
- Section 3.1.2 Data
- Section 3.1.3 Numerical Modeling
- Section 3.1.4 Conceptual Models
- Section 3.1.5 Source Term

- Section 3.1.6 Geochemistry and Microbiology
- Section 3.1.7 Organization and Communication.

As discussed above, Section 3 in this final version of the Vadose Zone Deficiencies document is based on the consensus reached at the Vadose Zone Workshop. A recommendation of the workshop included sorting the deficiencies into subject areas. The seven subject areas of deficiencies in vadose zone scientific understanding, as identified at the workshop, are presented below.

3.1.1 Spatial Variability

Spatial variability was identified as the most significant deficiency in INEEL vadose zone understanding.

3.1.1.1 Summary. No accepted method exists for addressing in fate and transport modeling the effects of spatial and temporal variations. Inherent heterogeneity of soils, sediments, and rocks at widely different scales (ranging from molecular to the tens of kilometers) and nonuniform areal distribution of precipitation and infiltration cause deviations from ideal transport behavior in the vadose zone. Because of these heterogeneities, the properties that affect solute transport and the physical, chemical, and biological properties of materials can be expected to vary spatially in the subsurface. The relative significance to water and solute transport of different scales of heterogeneity is unclear, but Wood and Norrell (1996) have reported that greater scales of observation result in more extreme variability of flow phenomena. Faybishenko et al. (1998) proposed a hierarchy in which different flow models are used for different scales of investigation but found no evidence of scaling principles that would allow prediction of effects at one scale from observations at another.

Preferential flow, the process by which water and solutes move by preferred pathways, or fast paths, through a geologic medium (Helling and Gish 1991), presents one of the biggest dilemmas for monitoring in the vadose zone. Preferential flow in both fractured rock and soil is well documented and local wetting fronts may propagate to much greater depths than predicted, essentially bypassing the matrix pore space (Beven 1991). In Figure 1, a photograph is provided as evidence of preferential flow (finger flow) from a laboratory experiment of slow infiltration into a 1-m-diameter column packed with uniform quartz sand. Mechanisms for preferential flow in fractures include event-driven flow, film flow, and chaotic flow.

Event-driven flow occurs at the INEEL only sporadically under special circumstances such as during flooding or increased infiltration because of major thunderstorms, unusually heavy snowmelt or high flows in the Big Lost River. Film flow, a process hypothesized to occur in fractures, occurs when a film of water of sufficient thickness forms on the fracture walls and flows under the influence of gravity. With thickness of at least 0.3 μm, films flow at rates of meters to tens of meters per day (Wan et al 1996). Because the relationship between moisture content and permeability of partially saturated rocks and soils is nonlinear (Pruess and Tsang 1990; Persoff and Pruess 1995), the flow processes in the vadose zone also are nonlinear. It is known from the theory of nonlinear dynamics (Abarbanel 1996; Tsonic 1992) that a combination of several nonlinear processes may lead to chaotic variations of the system parameters. In such systems, small changes in initial and boundary conditions may create new macroflow structures for different flow processes with no apparent scaling principles involved (Haken 1983).

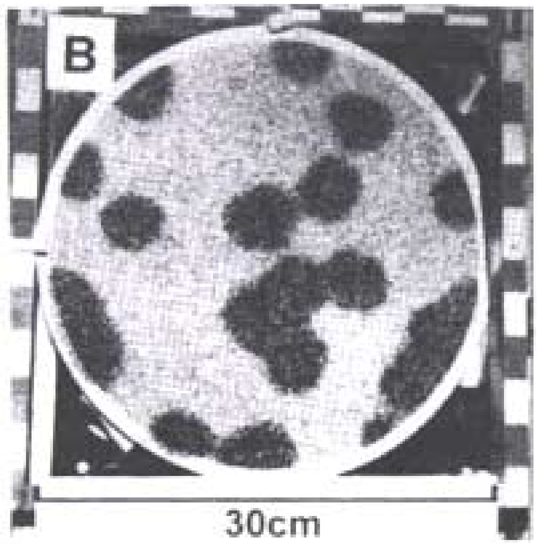

Figure 3-1. Finger flow demonstrated in a small lysimeter at a high (8.6 cm/hour) infiltration rate in quartz sand. The dye pattern shows evidence of unstable flow (Yao and Hendrickx 1996).

Because the relative volume of rock or soil occupied by the fast paths can be very small, and yet carry most of the water and solutes, the data from randomly installed sampling units may be extremely variable and completely unrepresentative of the spatial average (Kung et al. 1991). Water and solutes easily can bypass instrumentation and samplers (Biggar and Nielsen 1976), leading to erroneous conclusions about the spatial extent of contamination. Such bypassing largely invalidates potential schemes to scale up, or combine responses in a meaningful way, from point measurements or borehole measurements, and challenges the capabilities of known geostatistical methods. Some geophysical methods such as seismic surveys and cross-hole tomography can provide integration over large volumes but lack the resolution to reveal fast pathways.

3.1.1.2 Deficiencies. The deficiencies related to spatial variation identified during the Vadose Zone Workshop include the following:

- Knowledge is inadequate of spatial variability of hydraulic and transport properties and relative significance of spatial scales within INEEL sediment and volcanic rock units.
- No validated way exists to scale up laboratory-determined properties to field-scale conditions
- Ability is inadequate to incorporate spatial variability of lithology and hydrologic and transport properties in numerical models at the scale at which those properties can already be measured
- Knowledge is inadequate of the interrelationship and interconnectivity of various fracture sets in basalt lava flows and how they constitute the effective permeability

- Ability is inadequate to effectively assess the site-specific, three-dimensional distribution of basalts and sediments in the subsurface.

3.1.1.3 Recommendations. To address the identified deficiencies, INEEL scientists and managers should develop a field-scale vadose zone test bed or facility equipped for both characterizing the heterogeneities in INEEL-area subsurface materials and assessing the effects of those heterogeneities on transport. The test bed or facility should allow achievement of the following:

- Develop instruments for site characterization and monitoring and for measuring properties and flux in fast paths

- Improve understanding of preferential flow mechanisms

- Identify ways to determine the sample distribution required to represent a site

- Develop, in a generic sense, an understanding of the spatial variability effects on transport of water and contaminants

- Improve documentation and definition of existing heterogeneity and its impact on models

- Develop scale-up relationships for combining point measurements to represent a site

- Develop modeling approaches that account for individual flow paths

- Improve understanding of the facies distribution of sediments and basalts in the subsurface and obtaining data sets suitable for statistical analyses

- Develop tracer tests that integrate small-scale effects into large-scale flow and transport

- Design laboratory- and field-scale tests together to identify correlations between laboratory- and field-scale results.

3.1.2 Data

Lack of data was judged by the workshop participants as the second most crucial need.

3.1.2.1 Summary. Monitoring and sampling for laboratory determinations of hydraulic parameters have been conducted primarily in response to INEEL Environmental Restoration and Waste Management Program requirements for individual projects at various INEEL sites. The project requirements were developed in response to contaminant fate and transport modeling needs to meet specific regulatory milestones. Because the investigations are project driven, they tend to be of short duration over localized geographical areas. Project needs also have largely dictated the selection of monitoring and sampling parameters. Generally, the variables monitored in the field were moisture content, matric potential, perched water levels, and soil temperature. Laboratory-determined hydraulic parameters included moisture content, porosity, bulk density, moisture characteristic curves, saturated hydraulic conductivity, and particle-size analyses. The monitoring and sampling have focused on the surficial sediments, though some instrumentation has been installed to monitor the basalt and interbeds and a few samples have been collected from these materials. Vadose zone hydraulic investigations are described in detail in Appendices A and B.

The INEEL is heterogeneous relative to the surficial alluvium, the fractured basalts, and the sedimentary interbeds (see Section 3.4). The range in unsaturated hydraulic properties and the spatial distribution has not been defined or measured for the INEEL.

Project constraints and shifting priorities under changing management rather than science sometimes limit the continuity of long-term monitoring programs. The data that have been collected are probably not representative of the INEEL over time because of the gaps and short duration in the hydrologic data sets. These gaps are important because snowfall, the form of precipitation that generally has the greatest impact on infiltration, varies from year to year. Some years are wet, while most are dry. In a statistical analysis focusing on total snowfall, Dehaan[b] showed that monitoring had to be continuous over an 8-year period to have a 90% chance of collecting data from a "wet" year. Data from a wet year are important because they provide an upper range for the quantification of infiltration. A photograph of the INEEL Radioactive Waste Management Complex (RWMC) during a wet year (1995) is provided in Figure 3-2.

Figure 3-2. Photograph showing ponding resulting from an average snow melt over frozen ground at the Subsurface Disposal Area of the Radioactive Waste Management Area.

3.1.2.2 Deficiencies. Though the investigations sited above have generated greatly useful hydraulic data that have been valuable in understanding the hydraulic processes occurring in the INEEL vadose zone, deficiencies are associated with the data. The deficiencies in data identified in the Vadose Zone Workshop include the following:

- An insufficient number of laboratory and in situ measurements of hydrologic properties have been made at the INEEL

- Current vadose zone characterization and monitoring at INEEL facilities have led to discontinuous data sets that are unable to describe temporal variations in moisture behavior

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b. Dahaan, M. S., 1999, Interdepartmental Communication to C. W. Bishop, Lockheed Martin Idaho Technologies Company.

at depth in the vadose zone from transient infiltration events at the surface such as ponding or focused infiltration

- The discontinuous data sets are not of sufficient quality for use in calibrating numerical simulations to produce model results with adequate confidence

- Facilitated transport of actinides in colloidal form has not been evaluated at INEEL disposal sites.

3.1.2.3 Recommendations. The following monitoring and hydraulic analytical activities are necessary to provide adequate monitoring and sampling of hydraulic data:

- Develop a process to determine the sufficient amount of data to calibrate and validate transport models.

- Develop a monitoring network that is spatially representative of INEEL facilities.

- Collect data for a sufficiently long time to obtain a temporally representative data set.

- Develop a consistent set of monitoring parameters that will serve as basic monitoring parameters.

- Develop better monitoring instrumentation to permit monitoring in the preferred pathways such as fractures, interbeds, rubble zones in the basalts, and alluvial zones in the silty clay materials (e.g., interbeds and surficial sediments). Better monitoring instrumentation also should be developed to efficiently monitor a larger scale, giving information that represents the general vadose zone.

- Standardize monitoring instrumentation, installation, calibration, and data collection (to the extent possible) and adjust calibrations for scale.

- Monitor remediated sites to verify modeling and remediation effectiveness.

- Determine what constitutes the appropriate number and sample size for a representative sample collection, especially at depth.

- Develop moisture characteristic curves for semi-dense and dense basalts and for gravel.

- Conduct relatively large-scale natural gradient tracer tests to determine the large-scale effects of preferential pathways.

- Determine the geochemical conditions that lead to the formation of actinide colloids. The mechanisms for transport of colloids need to be better defined and related to the flow conditions present in the subsurface.

3.1.3 Numerical Modeling

Numerical modeling deficiencies were considered the third most crucial vadose zone deficiency at the INEEL.

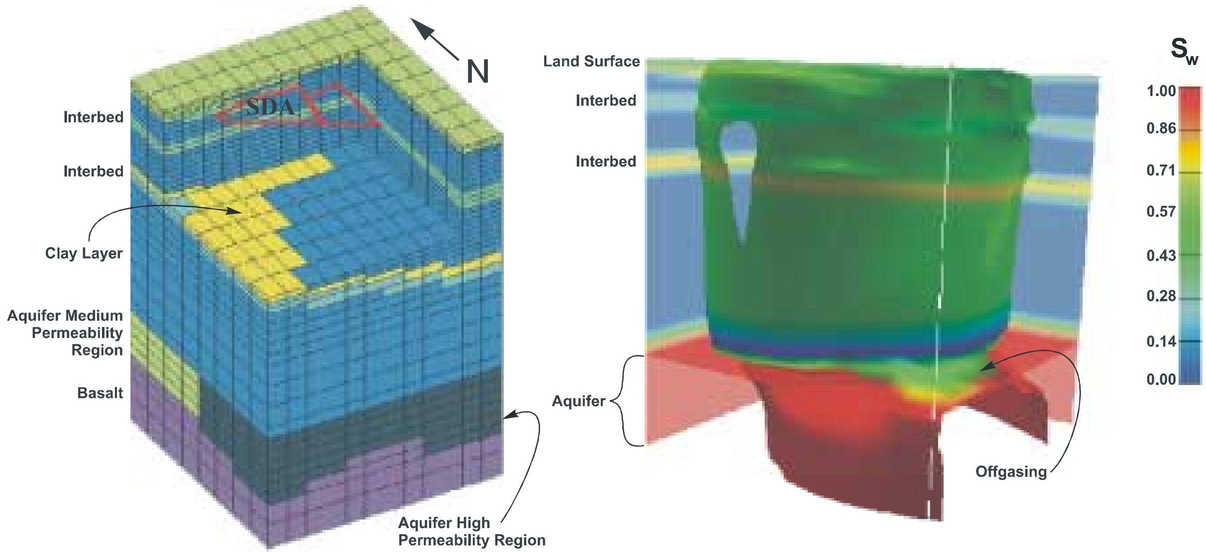
3.1.3.1 Summary. Predictive simulation studies of subsurface contaminant flow and transport at the INEEL and elsewhere are required to enhance the level of understanding of the mechanisms controlling flow and transport and to answer regulatory concerns about vadose zone contamination problems. Vadose zone contaminant concentrations are a source to the Snake River Plain Aquifer. Simulation studies are used to estimate groundwater concentrations as a function of time at hypothetical receptor locations.

In general, the contaminant flow and transport simulation process consists of the following:

- Developing a conceptual model of the physical and chemical processes governing flow and transport.
- Developing or selecting the appropriate governing equations for those processes (embedded in a simulator).
- Discretizing a domain of interest.
- Assigning model parameters to describe flow and transport properties over the model domain.
- Assigning initial and boundary conditions.
- Performing simulations.
- Comparing simulation results to field observations, a process generally referred to as history matching.
- Making decisions about revising the conceptual model, governing equations, parameters, initial conditions, and boundary conditions to improve agreement between simulated conditions and observed monitoring results. The result is a simulation model.
- Using the simulation model to predict the movement and future concentrations of contaminants in the subsurface.

The simulation process helps to identify the factors that are understood about subsurface flow and transport from available hydrologic and contaminant monitoring data and likewise the factors that are not understood about these same data. It provides guidance for conducting activities to improve understanding and prediction capabilities. An example application of flow and transport modeling is shown in Figure 3.

The conceptual models that have been employed in simulation studies at the INEEL have relied almost exclusively on the concept that the subsurface, including the fractured basalt, can be simulated as some sort of equivalent continuum. Equivalent porous media, dual porosity, and dual-permeability media have been used to represent the fractured basalt composing the majority of the vadose zone. Processes and parameters used in the simulation process are developed from a variety of sources. Though these are best developed from an understanding based on field observations, literature values and conservative estimates also are often used. The equivalent continuum approach is consistent with modeling studies performed across the DOE complex, including those conducted at the Yucca Mountain DOE site in Nevada (Pruess, Faybishenko, and Bodvarsson 1999). As at the INEEL, variably saturated flow and contaminant transport in porous fractured media are a primary concern at the Yucca Mountain site.



Cutaway view of Subsurface Disposal Area three dimensional grid with lithologic implementation.

Flow and transport simulation results showing carbon tetrachloride isosurface with water saturation superimposed.

Figure 3-3. Flow and transport modeling results showing an isosurface of carbon tetrachloride aqueous-phase concentrations in both the vadose zone and the underlying Snake River Plain Aquifer with water saturation superimposed.

A primary goal in the simulation process is the creation of numerical models that accurately represent contaminant transport at a facility. This goal has not been achieved at most INEEL facilities. The next section highlights current deficiencies in conducting simulation studies.

3.1.3.2 Deficiencies. The deficiencies identified during the Vadose Zone Workshop in vadose zone scientific knowledge that affect the ability to conduct representative simulations of subsurface flow and transport in the vadose zone at the INEEL include the following:

- The simulation studies have been primarily deterministic with only limited attempts at including uncertainty. This approach limits the usability of the simulation results for making environmental decisions.

- An emphasis should be placed on using probabilistic modeling and effective representation of the uncertainty in the simulation results. This emphasis will require collecting appropriate data to define parameter distributions.

- The applicability of Richard's equation should be evaluated to determine whether it appropriately describes water movement through unsaturated fractured basalts.

3.1.3.3 Recommendations. The following recommendations are provided to address the identified deficiencies.

- In terms of simulation capability, develop computationally efficient simulators to allow the discretization necessary to represent flow and transport in the complex and heterogeneous vadose zone at the INEEL. These simulators must be able to include the following:

  - Kinetic reactive transport
  - Facilitated transport
  - Dual-porosity, dual-permeability media
  - Efficient visual post-processing
  - Geostatistically based input of spatially varying properties, with explicit accounting and aggregation of uncertainties
  - Inverse parameter estimation techniques.

  Not all of these features will be found in a single simulation code. Rather, portions of the necessary features will be found in a variety of codes that have been developed already, and other features will be included in codes that are still in development.

- Develop improved data sets obtained at more closely spaced spatial intervals and over long time periods.

- Establish a process for facilitated approval and adoption of improved simulation codes for use at the INEEL.

3.1.4 Conceptual Models

Workshop participants voted the fourth most important INEEL vadose zone need to be deficiencies in the development of conceptual models that accurately reflect system processes.

3.1.4.1 Summary. The conceptual models that have been developed at the INEEL describe the geologic framework, hydrologic environment, transport mechanisms causing contaminant movement, and geochemical controls on transport mechanisms. These models represent the state of knowledge of the vadose zone and its geologic and hydrologic context at the INEEL. They are based on several decades of cumulative INEEL experience and on the state of scientific knowledge for each discipline. An example is shown in Figure 3-4 of a conceptual model of volatile contaminant transport from a disposal site at the RWMC through the vadose zone into the Snake River Plain Aquifer. The figure depicts the hypothetical influence of the predominant interbeds on diffusive transport at the approximate depths of 110 ft (i.e., the B-C interbed) and 240 ft (i.e., the C-D interbed).

3.1.4.2 Deficiencies. The deficiencies in vadose zone conceptual model scientific knowledge identified during the Vadose Zone Workshop include the following:

- Improved feedback between field observations and conceptual or predictive models must be implemented to examine the agreement of the data to the conceptual model

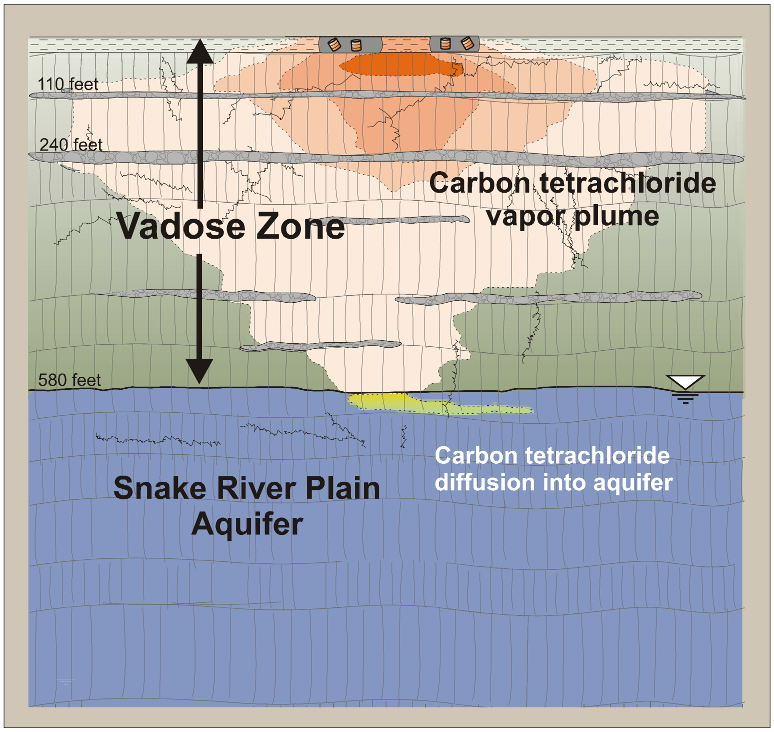


Figure 3-4. A conceptual model of volatile contaminant transport from a disposal site at the Radioactive Waste Management Complex through the vadose zone into the Snake River Plain Aquifer.

- Alternative conceptual models describing the following must be developed:
    - Flow and transport through fractured basalt rocks with sedimentary interbeds
    - Fracture-matrix interactions
    - Facilitated transport.

3.1.4.3 Recommendations. Understanding vadose zone processes sufficiently well to develop accurate conceptual models is the foundation of vadose zone science. To facilitate understanding, the following activities are recommended to address conceptual model deficiencies in scientific understanding:

- Collect sufficient baseline data for the system to be modeled
- Collect sufficient spatial and temporal data to characterize the modeled system
- Develop and test alternative conceptual models for geologic and hydrologic framework and transport mechanisms.

3.1.5 Source Term

Quantification of the various INEEL source terms for use in modeling was considered the fifth most crucial deficiency.

3.1.5.1 Summary. Models of contaminant transport through the vadose zone require source term input data, typically expressed as a flux of contaminants into the vadose zone. The accuracy of the source term data is often the most important factor affecting the overall accuracy of estimated risks associated with buried waste. Specialized source term codes such as Disposal Unit Source Term (DUST) (Sullivan 1993) and Breach, Leach, and Transport (BLT) (Sullivan et al. 1996; Sullivan and Suen 1989; MacKinnon, Sullivan, and Kinsey 1997) have been developed to generate source term input for the models. The models rely on empirically derived lumped parameters (e.g., distribution coefficients) to describe important physical and chemical processes, reflecting the limited understanding of these processes. A lumped parameter is a measurable quantity that may be affected by a number of causes with influences that cannot be resolved independently.

After burial, waste interacts with the surrounding backfill material, resulting in the release of contaminants to the vadose zone. The interactions that occur in and near the buried waste are dependent on both the conditions in the backfill and the properties of the waste.

The near-field environment is the region of disturbed soil around and including a waste form, such as the backfill within an auger hole or trench, that is affected by the waste form to comprise a distinct hydrological and chemical environment. Chemically and hydrologically, the near-field environment likely changes over time, and because of the different radiological half-lives (and, if they are known, chemical degradation rates), different contaminants will be released under different near-field conditions. For example, hydrologically, the most significant tritium releases from the beryllium blocks buried at the RWMC Subsurface Disposal Area probably occur within a decade of burial, when the soil disturbance caused by augering and backfilling still significantly affects vapor and probably liquid movement. However, the most significant ^{14}C releases (from a risk assessment point of view) may occur a hundred years after burial, at which time the backfill material may have the same hydrological characteristics as the surrounding soil. Again, using the buried beryllium as an example, the chemistry in the near field is affected currently by the presence of $MgCl_2$ (that is transported by liquid flow, a hydrological influence), the potential for galvanic corrosion because of the proximity of the beryllium blocks to their carbon steel containers, and the effect on the tritium release rate caused by accumulation of the beryllium corrosion products. The processes occurring in the near-field environment control contaminant release to the general vadose zone and must be better understood to reduce uncertainty in the source term.

3.1.5.2 Deficiencies. The deficiencies in vadose zone source term scientific knowledge identified during the Vadose Zone Workshop include the following:

- Currently, source term models treat water flow through the source term (i.e., the disposal pits) as a spatially uniform process despite the generally accepted conceptual model that water flow is nonuniform, event driven, and episodic.

- Information about the contaminant release mechanism and rate to the vadose zone is lacking. In the absence of data, conservative assumptions are used that can bias the eventual decision toward unnecessary actions.

- Appropriate measurement and model scales have not been determined to adequately characterize and model the source environment.

- Monitoring programs have not been designed to adequately characterize the source hydrology.

3.1.5.3 Recommendations. The following recommendations are provided to address the identified deficiencies.

- Conduct laboratory-scale experiments to evaluate model parameters that are relatively insensitive to scale and that may be evaluated adequately at a relatively small scale. If necessary, field-scale experiments should be conducted to evaluate parameters that have large-scale spatial dependency.

- Conduct a detailed study of near-field processes affecting the source term. The study would improve modeling of contaminant migration from existing buried waste. The timing for such a study is critical because various treatment and remediation methods for this waste are being considered for use at the INEEL. A better fundamental understanding of near-field processes can be used to develop effective treatment and remediation methods. Current INEEL projects that will require source term modeling include the Idaho Nuclear Technology and Engineering Center (INTEC) Tank Farm closure (DOE-ID 2000), the Organic Contamination in the Vadose Zone (OCVZ) project (Chatwin et al. 1992), and the Waste Area Group 7 comprehensive remedial investigation/feasibility study for waste disposed of in the SDA pits and trenches (Becker et al. 1998).

- Characterize water movement in the near field. The characterization would require instrumenting containers, waste forms, and backfill material within a few centimeters of the containers, as well as at more distant points within the disturbed backfill. The use of tracers should be considered. Some possible tracers that could be used include tritium as CFA water or a nonhazardous, stable, volatile organic chemical. The objectives of water movement characterization would include the following:

  - Testing the representativeness of current moisture monitoring of conditions in the near field

  - Developing a realistic model of water movement through or at the surface of waste

  - Defining the appropriate conditions for bench-scale tests of waste-material properties

  - Estimating (with tracers) the fractions of volatile species migrating to the atmosphere from buried waste.

- Characterize geochemical processes that occur in the near field that influence the mobilization of contaminants. These processes include the following:

  - The chemical capability of contaminants to form more or less mobile species

  - Facilitated transport (i.e., the association of contaminants with colloids)

  - Corrosion processes as they affect buried activated metal objects and containers

  - Characteristics of grout and waste treated by in situ vitrification

- Characteristics of water movement around waste treated by grouting or in situ vitrification.

- Refine analytical methods and models to account for advances in understanding of the processes that are found to substantially affect contaminant releases. A major objective for further study of the release of contaminants from waste forms is to improve the accuracy of source term codes such as DUST. More advanced source term codes should include features that allow more realistic modeling of near-field hydrology.

- Improve understanding of the following processes that would affect releases from grouted or in situ vitrification-treated waste:

  - The influence of the chemical environment within the grouted or glassified waste form on mobility of contaminant species

  - The relative importance of diffusional and dissolution-limited releases from grouted or in situ vitrification-treated waste in the initial monolithic form and as cracking and degradation progress

  - The effects of waste treatment on hydraulic properties within the treated waste at interfaces between treated waste and the surrounding medium and in cracks or other openings through the treated waste.

- Collect sufficient data to adequately characterize and model the source hydrology.

3.1.6 Geochemistry and Microbiology

Together geochemistry and microbiology were the sixth most important INEEL vadose zone deficiency identified at the Vadose Zone Workshop. Each is discussed separately in the following sections.

3.1.6.1 Geochemistry. As water moves through the vadose zone, it carries dissolved chemicals. The chemicals do not necessarily migrate at the same rate as the water because of geochemical reactions between the solution, solid soil minerals, and the soil-gas phase. The interaction between dissolved contaminants in solution and solid phases in the vadose zone is most commonly described using a single, empirical distribution coefficient or K_d. Significant changes can occur in vadose zone solutions making explicit geochemical analysis important in fate and transport assessments. The use of a linear, reversible, constant adsorption coefficient does not explain the many processes controlling contaminant migration, particularly near the contaminant source. New approaches are required to explain the geochemical reactions.

3.1.6.1.1 Geochemistry Summary—Geochemical reactions that control the fate and transport of contaminants through the vadose zone depend on the geochemical environment. The evolution and propagation of geochemical environments in the vadose zone depend on a complex interaction of hydrologic, biological, and geochemical processes:

- Plant root respiration and microbial degradation of organic matter raise the partial pressure of CO_2 in the vadose zone to 3 to 30 times greater than the concentration of CO_2 in the atmosphere. The proportional increase in CO_2 relative to depth is illustrated in Figure 3-5.

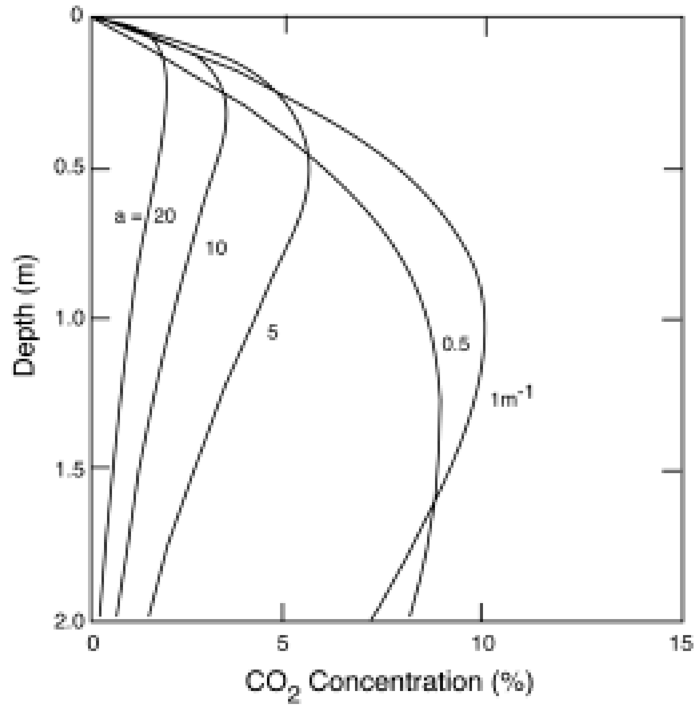


Figure 3-5. Calculated soil profiles of carbon dioxide in the soil zone for different depth distributions of the carbon dioxide production function. Carbon dioxide levels in the soil are sensitive to the depth of maximum carbon dioxide production (Suarez and Simunek 1993).

- The two environmental factors that directly affecting the rate of biological activity most significantly are the moisture content of the soil and the temperature of the soil.

- The dissolution of basic rock minerals by dilute carbonic acid controls the composition of natural waters. The pH of the water is determined by the balance between the dissolution of carbon dioxide from the gas phase and silicate and carbonate minerals from the rock matrix.

  Microbes in the vadose zone consume oxygen while converting soil organic matter to energy. In arid vadose zone environments, open pore space generally is sufficient for diffusion of oxygen from the atmosphere to maintain oxidizing conditions in the vadose zone. If the level of organic matter in the soil is high, or if pore space is filled with water, oxygen consumption may exceed replenishment through diffusion and reducing conditions may develop. If oxygen is depleted, microbes will use other inorganic compounds as electron receptors.

- Metals and radionuclides form soluble complexes with hydroxide, fluoride, phosphate, carbonate, and other ligands in solution. Waste may contain ligands such as ethylenediaminetetraacetic acid (EDTA), citrate, and oxalate from decontamination solutions. The extent to which complexes are formed can affect the ability of contaminants to adsorb from solution.

- Metals and radionuclides partition between the solution and mineral phases by adsorption reactions on the mineral surfaces. These adsorption reactions occur because of electrostatic effects (i.e., ion exchange) and because of specific chemical reactions (i.e., surface complexation). Surface adsorption reactions are the most important reactions for limiting the mobility of contaminants in the vadose zone.

- Plutonium has been determined in laboratory studies and field sampling programs to form colloids in water. Colloids are not reactive with exchange sites on rocks and minerals and have the potential to migrate at essentially the same rate as the water moving through the vadose zone.

- Acidic and basic waste solutions released to the vadose zone become neutralized through reaction with soil mineral phases.

- Solid phases in waste may dissolve over time, releasing contaminants to vadose zone solutions. Solid phases may precipitate from solution controlling solute concentrations by mineral solubility rather than by adsorption.

In general, performance assessment and risk assessment models typically do not address geochemical environmental factors, which can significantly impact transport.

3.1.6.1.2 Deficiencies—One deficiency in vadose zone geochemical scientific knowledge was identified during the Vadose Zone Workshop:

- The use of linear, reversible sorption (i.e., the empirical distribution coefficient or K_d) as the mechanism governing the interaction between aqueous and solid phases during transport does not address specific geochemical adsorption processes.

3.1.6.1.3 Recommendations—Laboratory studies can measure parameters and develop theories of important reactions. Computer models can show the relative importance of processes. However, sampling and analysis of field sites are needed to provide information on the geochemical environment in the vadose zone and verification of the processes occurring in the field. The following specific recommendations are provided to enhance understanding of geochemical issues:

- Implement the surface complexation and ion exchange models as mass transfer reactions in fate and transport models and use them to replace the empirical K_d approach. A database of exchange constants for minerals and soils must be developed, and the relative selectivity of surfaces for metals and radionuclides should be determined. The models will still be empirical at this time because the selectivity coefficients and types of surfaces are not well known. These types of models are important to advance the level of modeling of pollutants and radionuclides in the environment and the effect of the geochemical environment on contaminant transport.

- Conduct a study of the processes and mechanisms controlling the propagation of pH in the vadose zone and ways to incorporate these processes into a predictive reactive transport code. Most geochemical codes can speciate metals or radionuclides given the pH, but cannot generate these environmental factors from mechanisms such as biological activity. The ability to calculate the gas-phase carbon dioxide concentrations mechanistically is important to developing a predictive biogeochemical model of the vadose zone.

- Evaluate the reaction kinetics and transport rates to select problems and situations in which reaction rates are important to understanding migration. Most vadose zone geochemical reactions important for contaminant transport appear to be relatively fast. Kinetics of adsorption reactions is generally complete in a matter of hours to a few days. This reaction rate is generally faster than the rate of water movement in the vadose zone permitting equilibrium in geochemical reactions to be approached. In the spring, rapid recharge of snowmelt can result in very fast movement of water through coarse-grained materials. Kinetic factors may play an important role in contaminant migration.

- Measure the potential complexing agents in soil and groundwater to evaluate the presence and identity of these agents. Thermodynamic data to calculate the ability of the complexing agents to sequester contaminants in solution are available for many complexing agents and contaminants. Laboratory work may be needed to develop thermodynamic data for other compounds. The persistence of these complexing agents in the vadose zone then needs to be evaluated to determine their persistence for contributing to transport.

- Evaluate the biogeochemical reactions in buried waste to assess the development of reducing conditions in waste and the use of other electron receptors than oxygen by microbes. The fate of contaminants in buried waste are closely linked to the oxidation-reduction (redox) environment and the redox state of the contaminants. This information can be used to develop release rates from buried waste.

3.1.6.2 Microbiology. Microorganisms exert a profound influence on the environment. For vadose zone study, two significant microbial activities are microbially influenced corrosion and biological modification of contaminant fate and transport. With the exception of the well-studied organic topsoil layer, the literature contains very little data on vadose zone microbiology. Reports on vadose zone microbiology indicate that relatively low levels of biomass are present and that the distribution of the biomass is generally unpredictable (Hersman 1997). The chief limiting factor on microbial activities appears to be water availability, though the effects are often indirect. For example, nutrient transport is a limiting factor rather than dessication (Frederickson et al. 1993; Holden and Firestone 1997; Kieft et al. 1993). It is likely that temporal variations in water availability, which are largely unstudied, may significantly alter the activities of microorganisms in the vadose zone (Brockman et al. 1992; Colwell 1989; Frederickson et al. 1993).

3.1.6.2.1 Microbiology Summary—Similar to other sites worldwide, scant data on the microbiology of the vadose zone at the INEEL have been produced. Verifying that microbes from a core sample actually originated from the subsurface and are not from the surface (e.g., drilling fluids) is a critical part of subsurface microbiology (Colwell et al. 1992) at the INEEL and elsewhere. Therefore, development of sampling methods is an important step. Colwell (1989) reported on the microbiology of three cores from the 240-ft sedimentary interbed (i.e., also referred to as the C-D interbed) at 70 m below ground surface (bgs) in the vadose zone near the RWMC. Cores samples were taken by air-rotary coring with prefiltered air, and aseptic core processing methods were employed to reduce the likelihood of sample contamination. Total cell counts for these deep, vadose zone sediments were about 3E+05 cells per dry gram, which was one order of magnitude lower than comparable surface soils (3E+06 cells/dry g) taken at this site. No culturable organisms were found in one core while the other two cores had 50 and 21 colony-forming units (CFU)/dry g, respectively, compared to 3.5E+05 CFU/dry g for surface soil at this site. The significance of this study was the documentation of the existence of viable microorganisms at depth in vadose sediments from an arid region. The percent of culturable organisms (CFU/total cell counts $\times$ 100) was very low ($<$ 0.05%) in the vadose sediments compared to the surface soils (approximately 10%). This low-percent culturability could be caused by (1) inadequacy of culture techniques in growing potentially viable organisms or (2) dead-cell biomass (i.e., the majority of the organisms were dead). Dead cells are usually rapidly metabolized in the environment; however, the generally unfavorable conditions at this location could have suppressed the rapid turnover of dead cell biomass. Colwell (1989) speculated that intermittent recharge events could provide nutrients and waters to sustain organisms in these sediments and provide a mechanism of cell transport for colonization.

Kieft et al. (1993) reported on the microbiology of cores taken in 1990 from Coreholes W01 and W02 at the site of the proposed New Production Reactor (NPR) east of the INTEC. These cores were collected by reverse-air circulation rotary coring using argon and were aseptically processed on site (Colwell et al. 1992). Data from multiple tracers of potential sample contamination indicated very high quality samples were recovered. In fact, no aerobic heterotrophic organisms were cultured from 10 cores taken from between 69.6 m and 139.9 m bgs. Despite the absence of culturable heterotrophs, an average of 1E+07 cells/dry g was reported for these cores. Activity measurements using ^{14}C-labeled substrates showed extremely low levels of mineralization, many below detection levels and all below 10% mineralization of the added labeled carbon. The values for culturable heterotrophs and activity were significantly less than values observed in vadose zone cores from sites at Hanford and the Nevada Test Site (Kieft et al. 1993). The significance of Kieft's study is the report of microbiology data from deep crystalline rock in the vadose zone and the near absence of activities detected in the laboratory with the methods that were used. Palumbo et al. (1994) examined these same samples for the potential for stimulation of by nutrients and water. A minority of the core samples responded positively to the addition of water while a slight majority responded positively to water plus nutrients. Palumbo et al. (1994) speculated that the low amount of carbon in these samples and the flux of that carbon in situ could limit microbial activities.

Rogers (1998) reported on the microbiology of a depth profile for cores taken from three coreholes in the eolian sediments overlying the basalt flows at the RWMC. Coring was done by hollow-stem auger, and an aseptic technique was used to collect subsamples from cores taken from less than 1 m to about 7 m bgs. The context for this effort was investigations into microbially influenced corrosion of buried waste containers. Heterotrophs and acid producers were commonly recovered from these samples while *T. thiooxidans* was not found, and only an occasional positive was observed for dissimilatory nitrate-reducing bacteria and sulfate-reducing bacteria. The data from the three coreholes suggest a small spike in numbers of heterotrophs at around the 2-m depth and then very low values down to about 6 or 7 m where the number of culturable heterotrophs noticeably increases. Work by Rogers also was reported in Mizia et al. (1999) in which the presence of microorganisms of different physiologies was assessed in soil samples and on metal coupons buried at 1.5-m and 3-m depths at the RWMC. Liquid and solid media enrichments showed that heterotrophic bacteria, acid formers, actinomycetes, and fungi were found in all soils and on all types of metal coupons. No dissimilatory nitrate-reducing bacteria or *T. thiooxidans* were recovered from soil or the coupons while sulfate-reducing bacteria were only found in the soil. The absence of dissimilatory nitrate-reducing bacteria and the presence of high levels of oxygen found by soil gas analysis indicated the predominance of an oxic environment. In situ microbial activity was inferred by decreasing O_2 and increasing CO_2 with depth in the soil profile.

3.1.6.3 Deficiencies. One deficiency in vadose zone microbiological scientific knowledge in microbiology was identified during the Vadose Zone Workshop:

- The relative importance of the effects of biological activity on the transport of contaminants is not well understood.

3.1.6.4 Recommendations. Focusing vadose zone microbiological activities on two overarching areas of study clearly will advance the level of knowledge of vadose zone microbiology at the INEEL:

- Develop an understanding of the basic distribution of microbial physiologies and the abiotic factors that control their distribution
- Develop an effective and efficient method for determining rates of in situ biologic activity.

Specific activities required to implement the two areas of study include the following:

- Thoroughly characterize the vadose zone microbiology of a research site (vertically and horizontally) so that sufficient data are produced to achieve the development of a conceptual model of microbial processes in the vadose zone at a particular site. Given the low-percent culturability of microbes observed in deep vadose core samples from the INEEL, emphasis on culture-independent techniques is particularly warranted to explore basic and applied implications of high numbers of cells that cannot be cultured. In a ranking of environments for microbial activity, deep arid vadose zones rank near the lowest of those investigated (Onstott et al. 1999) and require that special attention be given to method detection limits.

- Conduct temporal studies incorporating alterations in water availability (natural or manipulated) to allow a full appreciation of the range in activities that may be exhibited. This characterization might be tuned to specific issues of concern, for example, microbial corrosion of buried waste containers or contaminant fate and transport.

- Develop accurate measurement methods for in situ microbial processes. Accurate measurement of microbial processes has proved to be nearly unattainable in all settings including the vadose zone. In the saturated zone, geochemical analyses of groundwater can assist in bounding rates of biological transformation. In the vadose zone, gases or mineralogical alteration could be examined. The work of Wood, Keller, and Johnstone (1993) offers a model for CO_2 measurement in the shallow vadose zone that could be adaptable to greater depths. Innovative approaches for assessment of in situ microbial activities are required for the vadose zone and other microbial habitats.

3.1.7 Organization and Communication

The Vadose Zone Workshop identified organization and communication as the seventh most serious INEEL vadose zone deficiency in scientific knowledge.

3.1.7.1 Summary. An effort supported by the INEEL Environmental Restoration Program Office is under way to develop an overall strategy to integrate vadose zone studies at the INEEL. The charter of this initiative will be defined by the INEEL vadose zone roadmap, for which this document is a key element.

Currently, vadose zone data are collected and funded at the project level. Integration of INEEL vadose zone activities would allow coordination of efforts for enhanced characterization, sustained vadose zone monitoring, and vadose zone research. Integration also would allow incorporation of new and innovative science and technologies into INEEL vadose zone projects and ensure that standardized methodologies and procedures are used to characterize and monitor the vadose zone. An example of an integrated vadose zone activity would be the implementation of a network of advanced vadose zone monitoring stations in key locations at waste sites to collect both chemical and hydrologic data routinely for a sustained period of time (a minimum of 10 years). By integrating vadose zone activities, research activities would be coordinated between the U.S. Geological Survey, site contractors, and universities to ensure that needs and uncertainties about the vadose zone are addressed.

On another level, integration from combined investigations must be achieved. A quote taken from the DOE Complex-wide Vadose Zone Science and Technology Roadmap (Schafer et al. 2000) illustrates this point:

> What experience does seem to indicate . . . is that site characterization [and subsequent vadose zone analysis] is an evolving, hypothesis-testing process that

accompanies iterative cycles of system conceptualization, measurement, prediction, observation, and model adjustment.

The more this cycle is repeated or augmented for a particular contamination problem, the greater the number of tools or technologies employed, the greater the number of interdisciplinary aspects of the problem considered, the better the understanding of the system, and the greater likelihood of making credible decisions about remediation or determining what new information or data may be needed . . . .

As a scientific process, this regime of activity is familiar. However, in the context of the vadose zone, its transition into an engineering practice is often hampered by the lack of complete experiments, technology demonstrations, and longer-term research through which holistic understanding of the vadose zone is improved . . . . Experience clearly indicates that these advances should be made in an integrated environment rather than occurring individually, allowing the transport and transformation processes to be more fully understood as opposed to developing a better understanding of individual components of each process.

Thus, in any vadose zone work, the combined results of many different analytical elements or perspectives should be used to better understand entire systems. Integration as defined here is the process by which an increased, enhanced, or unique understanding of system behavior is obtained through a combination of efforts that collectively exceeds their individual values when used alone. The goal, of course, is to perform the integration in a manner to maximize the information obtained from different elements . . . .

Integration should not be delegated to the end of the process. It should be considered from the very beginning starting with the theoretical and modeling work all the way through to the final analysis. In reality, the whole effort of understanding flow and transport in the vadose zone is reduced to effective integration of a diverse set of data and results derived from a multidisciplinary effort. The difficulty is not only integration, but also identifying the proper data and results to integrate.

3.1.7.2 Deficiencies. The specific deficiencies in integration identified during the Vadose Zone Workshop include the following:

- The INEEL lacks a coordinated, integrated means for coordinating vadose zone sampling, research and modeling above the project level

- A central archive is required to store and access data and analyses. A central archive would facilitate use of this information by DOE managers and contractors.

3.1.7.3 Recommendations. Integration of vadose zone activities is required at the INEEL to coordinate science and technology activities between the INEEL Site contractors, universities, other researchers, and the U.S. Geological Survey to guarantee that the deficiencies in understanding about the INEEL vadose zone are addressed. Integration between site programs could ensure complete data collection and model verification. Integration also is needed to oversee the incorporation of new and innovative science and technologies into INEEL vadose zone project approaches and ensure that standardized methodologies and approaches are used to characterize and monitor the vadose zone. In addition, integration should reduce the resource requirements necessary to conduct vadose zone characterization and monitoring at the INEEL and thereby produce cost savings.

Some of the specific means to address the deficiencies include the following:

- Incorporate vadose zone monitoring as an integral part of the assessment and cleanup effort for all major operable units. Currently, levels of vadose zone characterization and monitoring are inconsistent from one operable unit to the another. For instance, a limited effort has been expended for vadose monitoring at Waste Area Group (WAG) 7, the RWMC, yet virtually nothing has been done to collect vital vadose zone data at WAG 3, the INTEC.

- Coordinate and integrate vadose zone efforts between WAGs and standardize characterization and monitoring methods. An organized effort, funded for several years, could be used to support the development of nested projects where step-wise progress is made in vadose zone knowledge by causing the results from one test to feed into the next test at another WAG.

- Improve the collective INEEL ability to predict contaminant migration and in particular actinide mobility in the vadose zone. The observations of plutonium and americium in samples taken from interbeds and groundwater at the INEEL suggest that actinide mobility is greater than normally assumed. Such mobility also has been observed at Los Alamos National Laboratory, the Nevada Test Site (Discover 1999), the Hanford Site (GAO 1998), Clemson University (Newman et al. 1995), and in field- and laboratory-scale experiments conducted at the INEEL (e.g., Wood and Norrell 1996).

- Apply innovations in vadose zone characterization, monitoring, modeling, and remediation to all ongoing projects at the INEEL.

- Implement a coordinated effort in landfill cap analysis. This effort would including cap modeling, infiltration monitoring at currently capped sites, and use of the three existing facilities, the Protective Cap/Biobarrier Experiment (see Appendix D), and the Engineered Barrier Test Facility, to develop reliable predictions of long-term cover performance as well as estimates of net infiltration on disturbed sites at the INEEL.

- Establish closer ties between the INEEL and other DOE sites and the DOE complex-wide Vadose Zone roadmap project to facilitate the exchange of site characterization and vadose-zone transport modeling efforts. The INEEL vadose zone efforts would benefit from more frequent interactions with peers at other Western DOE sites (e.g., the Hanford site, Los Alamos National Laboratory, Yucca Mountain, and the Nevada Test Site) because workers at these sites are currently grappling with many of the same site characterization, monitoring, and modeling challenges as at the INEEL.

- Evaluate past vadose zone characterization activities, remedial actions, and monitoring at all INEEL sites and at similar sites at other western DOE facilities to determine the current best solution for a variety of sites. A goal of this effort would be to establish a knowledge base from which to direct additional research on monitoring and characterization.

3.2 Science Plans to Address Deficiencies Identified at the INEEL Vadose Zone Workshop

Draft outlines were prepared to guide the preparation of the science plans for each of the seven subject areas discussed above to address deficiencies in understanding of vadose processes (see Section 3.1). Initially, the intent was to prepare science plans for each of the seven subject areas of deficiencies discussed above; however, to enhance manageability some of the deficiencies were combined. Therefore, five science plans are being prepared for the following topics: (1) spatial variability, (2) characterization and monitoring, (3) flow and transport modeling and physics of flow, (4) source term, and (5) geochemistry and microbiology.

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Appendix A

Idaho National Engineering and Environmental Laboratory Vadose Zone Test Site Studies

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Idaho National Engineering and Environmental Laboratory Vadose Zone Test Site Studies

A1. LARGE-SCALE AQUIFER PUMPING AND INFILTRATION TEST

Characterizing the fundamental flow and transport properties of the vadose zone, that portion of the subsurface pathway between land surface and an underlying aquifer, is required to provide adequate information for determining long-term risk to humans and for evaluating remediation alternatives. Before the completion of the many laboratory and field tests conducted at the INEEL, parameters required for estimating contaminant transport rates in the vadose zone and groundwater were derived from limited laboratory- and small-scale field experiments, U.S. Environmental Protection Agency (EPA) publications, and literature values. When these parameters are unknown or large uncertainty exists, conservative estimates are used because of the importance of the results for making decisions that may have affected the health of nearby populations.

Historically, adequate technologies and methods have not been available to evaluate the movement of water that carried contaminants through fractured rock in the vadose zone. Therefore, several integrated projects were designed by the Idaho National Engineering and Environmental Laboratory (INEEL) Environmental Restoration Program to develop and test these technologies and to provide actual field measurements of in situ hydraulic and geochemical properties in the subsurface. These measurements provide the basis for INEEL calibration transport models.

The first major integrated INEEL project for meeting the various data and technology needs was the Aquifer Pumping and Infiltration Test (APIT) (See Figure A-1.) This test consisted of a 600-ft diameter pond, 4.5 ft deep with 67 monitoring wells in and around the basin. The wells were instrumented with lysimeters and transducers and provided access for neutron logging and bailer sampling. A test well was pumped at 2,800 gpm with an average of 500 gpm piped into the pond for 36 days. Short-lived radioactive tracers were added to the water in the pond to act as surrogates for radioactive waste.

Figure A-1. Aerial view of the Aquifer Pumping and Infiltration Test site.

The APIT project was designed to integrate the development and testing of new technologies with the programmatic data needs. Table A-1 describes the programmatic data needs for modeling.

Table A-1. Unsaturated and saturated data requirements for the Aquifer Pumping and Infiltration Test.

	Contaminant Transport	
Data Requirements	Unsaturated	Saturated
Partitioning Coefficients Description of the equilibrium partitioning between dissolved contaminants and contaminants sorbed to the geologic matrix.	√	√
Dispersivity Defined as a factor related to the lateral and longitudinal spreading of contaminants during advective transport. Typically dispersivity is used to fit model results to existing plume geometry.	√	√
Effective Porosity Measure of the percentage of interconnected void space.	√	√
Unsaturated Hydraulic Conductivity Nonlinear variable describing the ability of subsurface material to transmit water as a function of moisture content.	√	
Aquifer Transmissivity Measure of the ease with which an aquifer can transmit water.		√
Aquifer Storage Coefficients Measure of the ability of an aquifer to store or release water.		√
Moisture Flux Moisture content on a multiyear basis defining the advance of wetting front and recharge available for contaminant transport.	√	
Anisotropy Measure of the tendency for preferential flow in an aquifer.		√

Various monitoring devices for the unsaturated zone have been in use for many years. Most of these devices originated in the soil and agricultural sciences and were not directly transferable for use in fractured rock formations. At the INEEL, in situ instrumentation was needed to monitor moisture movement, collect unsaturated zone water samples, and monitor contaminants moving through the arid, fractured rock vadose zone. In addition, methods were needed and developed for installing and isolating these devices in fractured rock and sealing the boreholes to prevent piping water down the side of the well. The APIT project was the mechanism for testing the instrumentation and collecting field data at a representative scale of the contaminated sites at the INEEL. The instruments and methodologies that were developed and tested during the APIT are listed in Table A-2.

Table A-2. Technologies developed and tested during the Aquifer Pumping and Infiltration Test.

Technology	Application
Cross-Hole Radio Tomography	First successful application of this technology to fractured basalt. Differencing between pre-wetting and post-wetting conditions delineated moisture increase between boreholes.
Deep Lysimeter	Successful installation at depth to collect water samples in unsaturated conditions in fracture zones within the basalt portion of the subsurface.
Enhanced Neutron Probe and Neutron Logging Capabilities in Fractured Basalt	50 mCi and 3 Ci sources were calibrated to determine relative differences in moisture content in a fractured basalt vadose zone. In addition, an innovative field transport system was developed for rapid collection of CPN data from deep holes (+180 ft).
Surface Resistivity Imaging	Possibly the world's largest surface direct current resistivity array was constructed for the APIT. A differencing technique was employed to image the migration of perched water at a depth of 180 ft along the top of a sedimentary interbed. The surface resistivity also was used to infer structural changes in the geology.
In Situ Radionuclide Assay System	An advanced downhole logging technique was developed to monitor radionuclide tracer migration during the test. Full gamma spectrums allowed speciation of several radioactive tracers at discrete depths in real time. Additional development of this instrument now allows measurement of downhole gamma, beta, and alpha radiation.

Experienced gained during the APIT provided an excellent foundation for understanding flow in an arid, fractured rock vadose zone and demonstrated the need for a standard approach and a set of tools for characterization and monitoring of arid, fractured rock environments. To support this approach, a suite of tools was required to collect transport parameters in fracture rock. Through collaboration with the Lawrence Berkeley National Laboratory, Stanford University, Parsons Infrastructure and Technology, and the INEEL, the Analog Site for Fracture Rock Characterization Project was developed. The project was designed to address the problem of characterizing contaminated fractured rock. The project involved developing an approach and technologies for defining a site conceptual model in an arid, fractured rock vadose zone. This approach is transferable to conceptual model development of contaminated sites for predicting future behavior and design effective remediation schemes under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (42 USC § 9601 et seq.).

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A2. BOX CANYON

A2.1 RWMC Vadose Zone Basalt Characterization

Geostatistical studies were carried out at Box Canyon of the Big Lost River and at the Hell's Half Acre lava flow by Knutson et al. (1990) as an analogue of basalt in the vadose zone beneath the Radioactive Waste Management Complex (RWMC). This effort analyzed trends in the three-dimensional variability of the basalt flows and provides the best geostatistical data set available for Snake River Plain basalts. It also was supported by laboratory and field experiments to measure hydraulic conductivity.

The basic geometry of the flows is not planar stratified, but rather, a complex interfingering of lobes. The ratios of thickness to length of the flow lobes were measured and found to have a median length to width to thickness (or height) ratio of more than 8.4:4.6:1. Thus, the median flow thickness from the core data results in flow dimensions of the order of more than 130:69:15 ft (more than 40:21:4.6 m). Despite heterogeneity in flow morphology, the flows usually can be differentiated into four horizontal elements: (1) substratum, (2) flow base, (3) central zone, and (4) upper zone.

The substratum may be a rubble or brecciated layer, a baked sediment layer, or a covered pahoehoe surface. In many cases, this substratum may be one of the most transmissive elements in the flow sequence. This high-porosity layer also has a very low bulk density.

Flow bases are generally vesicular and jointed. The moderate degree of vesiculation produces moderate porosity, median value 20%, and bulk density, median value of 2.41 g/cm^3. The jointing is perpendicular to the surface and has a polygon width to height ratio (W/H) of 0.5 to 1. This results in a median distance between fractures of approximately 1.7 ft (0.5 m).

The central zone is generally jointed with a median discontinuity. This zone is massive, with a few bubble plumes or bubble tracks marking the rather plastic internal flow layer boundaries. Thus, it has low porosity, median value 10%, and high bulk density, median value of 2.73 g/cm^3. The jointing is perpendicular to the cooling surfaces and has a polygon W/H ratio of about 0.5, with a median distance between fractures of about 4 ft (1.2 m).

The upper zone generally is layered parallel to the surface and has a vesicular texture and finely jointed crust. It has high porosity, median value 21%, and low bulk density, median value of 2.40 g/cm^3. One or more partings can develop parallel to the surface, and columnar jointing is common in the crust perpendicular to the surface. A polygon W/H ratio of about 0.5 is common. The most common geometry is a thin crystal element with fracture spacing of about 0.8 ft (0.2 m) and a coarser, more pervasive fracture set with a spacing of about 3 ft (0.9 m).

The basalt porosity and permeability plots for the flow sequence are usually "shotgun" patterns indicating a complex flow mechanism (Knutson et al. 1990). The petrography provides some insight into this mechanism. The high-permeability vesicular basalt (up to 5,000 millidarcys (md) generally has a fine-grained, crystalline matrix and vesicles of irregular size and shape. The low-permeability vesicular rock (a few millidarcys or less) has glassy or partially oxidized opaque vesicle walls, which are generally regularly shaped and sized. Thus, the permeability is usually controlled by the characteristics of the cavity lining and the rock matrix connecting the vesicles. The lower-permeability, nonvesicular core (a few millidarcys or less) generally has an intergranular matrix with relatively small, regularly sized, nonconnected pores. The more permeable material (5 to 10 md or higher) has somewhat larger, irregularly sized, more frequently connected pores. Permeabilities and the percentage of visible pinpoint porosity noted in the core descriptions correlate closely. The low-porosity central zone has the highest median permeability.

Geostatistical studies also were performed at the Hell's Half Acre flow to obtain flow-top geometries, flow-thickness variations, and flow-top characteristics. Flow-top studies resulted in variograms that can be used to evaluate kriging results for flow-top geometries and flow thickness variations at the RWMC. Measurements of flow-top characteristics indicated that smooth-uneven surfaces occur 51%, fracture-fissures 19%, rubble 17%, and bouldery, blocky, and broken surfaces 13% of the time.

Most of the work for the Analog Site for Fracture Rock Characterization Project was conducted at the Box Canyon site, which is 7 mi west of the INEEL near Arco, Idaho. The geologic investigation of the basalt set the stage for developing an analog for fractured rock characterization. The pattern of fractures formed in Snake River basalts was quantified and analyzed to predict the nature of fluid flow in these rocks. Geophysical techniques were brought into the program to help image important features and processes in the rocks. A variety of electrical, radar, and seismic methods were evaluated. An innovative pilot application of inverse analysis to the APIT data set was used to demonstrate an alternative to conventional aquifer test analysis. The inverse method attempts to identify connected fracture networks that explain the well test data simultaneously. This demonstration was successful. Another task in the Analog project was a pilot study of the use of isotopic data in conjunction with hydrologic data to identify fast-flow paths on the aquifer scale. An aerial photograph of the Box Canyon site is provided in Figure A-2.

Figure A-2. Box Canyon site.

The primary purpose of the field testing at the Box Canyon site was to understand contaminant transport in the fractured basalt vadose zone beneath the INEEL. The first efforts focused on the geologic structure and fracturing of the subsurface. The Box Canyon site was chosen because the fracture system is exposed on the surface and in vertical cliffs along a river. Because of the excellent exposures, this site was used to test characterization techniques, methods, and instruments. Arrays of vertical and slanted holes were drilled back from the cliff face to further characterize the subsurface using geophysics, core-data and prototype vadose zone instruments. A series of infiltration tests were conducted with monitoring in boreholes, the surface, and the cliff face to determine how water moves downward.

The INEEL also developed several patented instruments under the Analog Site Project. The foremost of these was the Advanced Tensiometer (Hubbell and Sisson 19998), which was awarded the *R&D 100* award in 1997 (LMITCO 1997). A field site was developed adjacent to the Idaho Research Center for instrument testing and design. The plot consists of six shallow borings for testing various vadose zone instruments.

The analog site project was provided with database management and visualization systems tools capable of integrating large complex data sets in a three-dimensional representation by a state-of-the-art visualization program developed through U.S. Department of Defense funding.

Research at the Box Canyon site and the subsequent data analysis suggested that traditional methods and paradigms (e.g., Darcy's law and the Richards' equation [1931]) are inadequate at this scale for predicting fluid migration in fractured vadose zones. Traditionally, these systems are described in terms of parameters that reflect average behavior that does not adequately describe the complex geometry and time-dependent physical processes. In the Box Canyon studies, observations suggested that flow under variably saturated conditions is a chaotic process.

A3. HELL'S HALF ACRE

Evidence for chaotic behavior in unsaturated fractures has been documented in the laboratory (Nicholl et al. 1994) and field experiments (Long et al. 1995). These concepts may help to explain what is happening in multiphase flow and transport in fractured rock.

Algorithms, which capture the inherent dynamical nature of the phenomenon of infiltration in fractured rock, could predict an attractor that describes all the possible states of flow and transport conditions over time and space. It is common for chaotic-dynamic systems to exhibit bounded attractors, implying that useful bounds can be placed on long-term predictions of future system behavior, despite the limitation of the ability to predict specific behavior. Thus, if an attractor or family of attractors could be defined for contaminant transport in fractured rock, bounds could be placed on the future behavior of the system. The bounding capability would greatly simplify the traditional numerical predictions in use today for assessing risk from contaminant waste sources. The "A Chaotic-Dynamical Conceptual Model to Describe Fluid Flow and Contaminant Transport in a Fractured Vadose Zone" project strives to define an attractor or family of attractors for fluid flow in fractured rock. Research at the Hell's Half-Acre site grew from the necessity to collect detailed information from a natural fracture system at a scale intermediate between laboratory tests of artificially constructed fractures and full-scale field tests. Information from the laboratory tests, full-scale field tests, and burial sites at the INEEL were used in the design and implementation of the Hell's Half-Acre tests. An apparatus for measuring flow and transport in vesicular basalt at the Hell's Half Acre site is shown in Figure A-3.

The Hell's Half-Acre research site was selected because of the near-surface exposure of relatively young basalt that has not undergone extensive weathering and sedimentary infilling compared to the older basalts at Box Canyon. The site is located in the Hell's Half-Acre lava field, near Shelley, Idaho. The

Figure A-3. Apparatus for measuring flow and transport in vesicular basalt at the Hell's Half Acre site.

research site consists of two heavily instrumented overhanging basalt blocks on the edge of a collapsed lava structure. The two basalt blocks under investigation are approximately 1 m in thickness and allow access to the upper and lower surface of the fractures under investigation. Numerous tests have been conducted under constant head conditions and constant flow conditions. Interpretation of the data is ongoing, and preliminary results have delineated a chaotic component to the fluid migration.

Vadose zone basic and applied research at the INEEL often develops from needs identified during site investigations at the INEEL and other DOE sites. Continued funding of these projects promises to advance the scientific understanding of fluid migration in fractured rock and reduce the uncertainty in predictions of contaminant fate and transport.

A4. ENGINEERED BARRIER TEST FACILITY

A surface cover-testing program is currently under way at the INEEL. The program is designed to provide data required to evaluate options for closure of the low-level radioactive waste pit at the RWMC and other waste disposal areas of the INEEL. The current phase of testing is evaluating the response of two different storage-evapotranspiration type covers to extreme wetting conditions. The hydraulic and structural responses of the covers to extreme events and their subsequent recovery are pertinent to the long-term (i.e., 1,000 years) performance and risk assessments of the covers.

The surface covers are being tested at the Engineered Barrier Test Facility located adjacent to the RWMC in the southwestern corner of the INEEL. A schematic of the Engineered Barrier Test Facility is provided in Figure A-4. The proximity of the Engineered Barrier Test Facility to the low-level radioactive waste disposal pit at the RWMC enhances the opportunity for testing the barriers under site-specific conditions. The facility is a concrete structure consisting of five cells (plots) on either side of an enclosed access trench. Each cell has four walls and a floor and measures 3.05 m wide by 3.05 m long by 3.05 m deep. The top of each cell is open to the atmosphere. Because of shallow soil at this location, soil is bermed up around the facility so that cell tops are slightly above grade level. Each cell has two floor drains that empty into separate sumps in the access trench. One drain drains a 10-cm wide trough that extends around the bottom perimeter of the cell. The other drain drains the remaining central portion of the cell. Each drained area is sloped toward its drain.

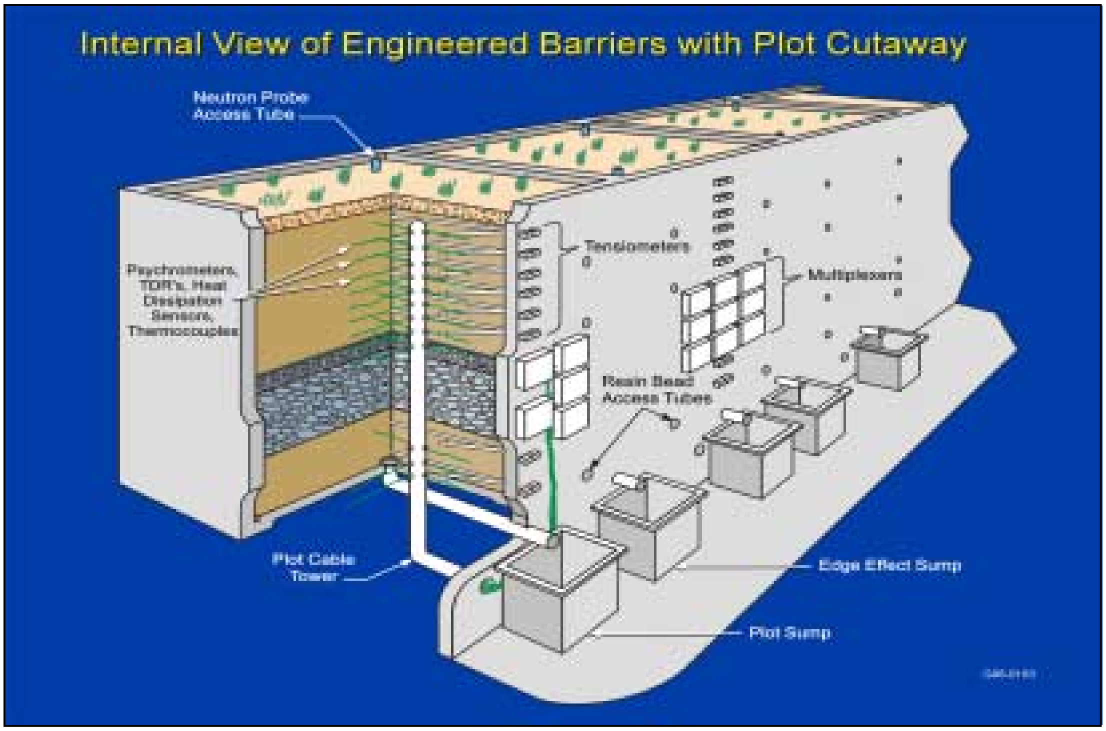

Figure A-4. Schematic of the Engineered Barrier Test Facility at the RWMC.

The access trench is approximately 26.2 m long by 3.0 m wide by 3.8 m deep and serves primarily as a protected area for housing the data acquisition system and those instruments (e.g., tensiometers) that penetrate the cell walls. A separate room at the south end of the access trench houses the data acquisition computer and serves as an office area. The access trench is supplied with 115-V electrical service and a telephone line. A heat pump mounted on the south end of the roof of the access trench minimizes temperature variations and prevents freezing within the access trench.

Replicates of two engineered barrier designs were constructed in the test cells. One cover design consists of a uniform layer of silt loam soil. This soil is covered with a 15-cm-hick layer of mixed silt loam soil (75% by volume) and gravel (25% by volume) designed to increase the cover's resistance to wind erosion. The other cover design consists of a similar soil-gravel surface layer underlain by 1.45 m of silt loam soil. Beneath this soil is a 15-cm-thick layer of gravel and a 76-cm layer of cobbles. A sharp interface between the gravel and the overlying soil is maintained by a high conductivity geotextile. The interface forms a capillary barrier that impedes downward water flow during unsaturated conditions. The cobble layer is intended to minimize biointrusion beyond this depth. The cobble layer is underlain by more silt loam soil. Both types of covers are designed to exploit the transpiration capabilities of plants to extract water that infiltrates into the covers. However, all test plots were maintained devoid of vegetation during the current testing period. The absence of vegetation allows evaluation of the behavior of the barriers under the most extreme hydrologic conditions that are likely to occur. Each test plot is heavily instrumented to continuously measure soil moisture, soil moisture tension, soil temperature, and drainage.

A wetting test designed to subject the covers to severe hydrologic stress was performed on all test plots in FY-97. Each wetting test consisted of applying water to the surface of the plot until drainage from the bottom of the plot began.

Test plot monitoring is providing continuous data depicting the dynamics of water movement within and through the covers and the structural response of the covers in response to extreme hydrologic conditions. Water-balance analyses based on the observed data have revealed significant differences between the performance of the thick soil and capillary/biobarrier test plots both before and after the wetting tests. The data led to a better picture of how the covers respond to and recover from extreme environmental impacts. Numerical modeling of the data is being used to evaluate the appropriateness of the models for describing the soil water dynamics and to provide a field data set for calibrating the models for making long-term predictions. Additional testing with modified boundary conditions is scheduled.

A5. U.S. GEOLOGICAL SURVEY STUDY

A5.1 Test Trenches

In 1985, the U.S. Geological Survey (USGS) installed two test trenches in a 61 × 46-m area in the surficial sediment near the northern boundary of the Subsurface Disposal Area (SDA) of the RWMC. The goal of the research was to obtain hydrogeological and meteorological data for disturbed and undisturbed sediments at the RWMC to evaluate the changes in physical and hydraulic properties of RWMC surficial sediments caused by the excavation and in-filling of waste trenches at the SDA. Properties measured in the study include texture, mineralogy, moisture content, and unsaturated and saturated hydraulic conductivities. The undisturbed profile was determined to be heterogeneous in terms of texture, mineralogy, and hydraulic conductivity, whereas the disturbed profile was relatively homogeneous relative to these parameters. Disturbed sediments were found to have generally higher porosity and hydraulic conductivity relative to the undisturbed samples. The undisturbed layer was found to contain a continuous layer with a high clay content at a depth of 140 to 220 cm. This clay-rich layer may act to slow downward moisture migration and, therefore, increase the effects of evapotranspiration. The destruction of this layer in the disturbed profile probably enhances vertical flow. Thus, the simulated waste trench may have wetter soil in the 3 to 6-m zone in which the waste is buried.

A6. LABORATORY STUDIES

Several INEEL vadose zone investigations have been cooperative ventures between the INEEL and universities. Some of the work has been thesis research leading to master’s degrees (Idaho State University and the Universities of Arizona and Idaho) while others have been ongoing project-funded investigations (Clemson University). Brief summaries of each of the pertinent investigations are provided below.

Most of the investigations have involved obtaining material from either the RWMC or the Central Facilities Area (CFA) landfills.

A6.1 University of Idaho Investigations

The earliest research was performed by J. V. Borghese for University of Idaho M.S. thesis requirements. The findings were published in *Hydraulic Characteristics of Soil, Cover, Subsurface Disposal Area, Idaho National Engineering Laboratory* (Borghese 1988). Borghese reported on hydraulic characteristics including saturated hydraulic conductivity, grain-size distribution, bulk density, and porosity of the soil cover at the SDA. The highest hydraulic conductivity values were determined for a depth interval of about 5 to 15 cm bgs.

L. F. Hall (1990) characterized physical properties of surficial soils at the CFA Landfill II and estimated annual infiltration. This investigation was a University of Idaho thesis project. The results of this study are reported in *Characterization of Soil Cover and Estimation of Water Infiltration at Central Facilities Area Landfill II, Idaho National Engineering Laboratory (INEL)* published in May 1990 (Hall 1990). Hall measured soil cover thickness at 60 locations and collected large undisturbed samples of course-grained soils using cheese-cloth and resin. Hydraulic conductivities ranged from 0.0020 to 0.0025 cm/second. Infiltration estimates ranged from between none to 4.56 in. per year, depending on the estimation method used.

A6.2 Idaho State University Investigations

In situ characterization of unsaturated hydraulic properties of surficial sediments adjacent to the RWMC was performed by J. F. Kaminsky (1991) for Idaho State University thesis investigation of surficial sediments. In the investigation, a field plot was used that was flooded for 24 hours, covered, and allowed to drain. Unsaturated hydraulic conductivity curves were obtained. Findings showed that unit gradient measurements can be substituted for the instantaneous profile measurements.

A6.3 University of Arizona Investigations

Hydraulic Properties of Vesicular Basalt (Bishop 1991) is a University of Arizona thesis study by C. W. Bishop. A vesicular basalt block was obtained from the RWMC and subsampled. More than 70 samples of the block were tested for saturated and unsaturated hydraulic properties including porosity, bulk and skeletal densities, pore surface area, saturated and unsaturated hydraulic conductivity, and moisture characteristic curves for the wetting and drying hysteresis limbs. Infiltration rates were measured for a large block of basalt. Bishop found that vesicular basalt has greater porosity than previously thought and that the basalt is not the barrier to moisture movement it was believed to be. A photograph of a laboratory apparatus for measuring hydrologic properties of basalt is provided in Figure A-5.

Figure A-5. Laboratory apparatus for measuring hydrologic properties of basalt.

A6.4 Clemson University Investigations

Clemson University and the INEEL have conducted column and batch tests to determine equilibrium distribution coefficients for americium, cesium, cobalt, strontium, uranium, plutonium V, and plutonium VI. The columns were packed with either INEEL crushed basalt or sedimentary interbed materials. The values obtained from the two methods were similar and did not vary greatly from values reported in the literature for similar conditions. However, a fraction of americium, cobalt, and plutonium applied to columns was transported at a faster rate than the bulk of these three radionuclides. Sorption rate constants were generally observed to be greater for interbed than for crushed basalt materials. Results also indicated that distribution coefficients measured under saturated conditions could be used to estimate retardation under unsaturated conditions. Results of this investigation are documented in *Evaluation of Mobility of Am, Cs, Co, Pu, Sr, and U through INEL Basalt and Interbed Materials: Summary Report of the INEL/Clemson University Laboratory Studies* (Newman et al. 1995).

A6.5 Deficiencies of the Laboratory Research

Many discontinuous laboratory projects produced site-specific data for specific areas at the INEEL. These data are then assumed to cover the entire INEEL site under all subsurface conditions. The INEEL subsurface is highly heterogeneous with variations between the surficial sediments from place to place depending on the sediment source and method of emplacement, variations between the basalt flows and within flows, and variations between the interbeds and within interbeds. The need is significant to continue these research investigations, integrate their findings, and to refine the data for specific conditions.

In addition, research was performed at laboratory scales. Currently, understanding is lacking of the relationship between laboratory scale and field scale; therefore, understanding is lacking of how to scale up the data. Relationships between the different scales are likely to be very different for the different porous media types found in the INEEL vadose zone. Deficiencies result from using crushed basalt as an analog for intact basalt. There may be little or no relationship between the two basalts, and coefficients developed for crushed basalt may not accurately describe intact basalt behaviors.

A7. COLLABORATIVE VADOSE ZONE RESEARCH SITES WITH THE UNIVERSITY OF IDAHO

A7.1 Troy Site

A number of field locations have been identified as potential research sites by the University of Idaho-INEEL vadose zone initiative alliance. Each of these research sites offers the opportunity to evaluate newly developed vadose zone instrumentation and monitoring techniques in an uncontaminated setting.

The Troy site near Moscow, Idaho, consists of an approximately 10-acre watershed and is an apparent analog site for sediment overlying a fractured basalt. The soil profile consists of a meter of sandy loam underlain by a fragipan layer (a dense low permeable soil with fracturing). The fragipan layer appears to act as a temporal impeding layer to infiltration. Initially, infiltration appears to penetrate the fragipan layer. At later time, the cracking in the fragipan appears to seal and acts as an impermeable layer. At present, approximately 100+ piezometers are instrumented with transducers and dataloggers to monitor temporal perched water conditions.

A7.2 Five Well Site

The Five Well Site is adjacent to the INEEL Rearch Center in Idaho Falls, Idaho, and has been previously used to evaluate the INEEL Advanced Tensiometer (Hubbell and Sisson 1998) in fractured basalt. Currently, the site has been selected as a research site to examine the spatial variability of infiltration into the fractured basalt. A nest of 20 tensiometer-piezometer has been proposed to monitor the distribution of the near annual perched water formation on the fractured basalt. Collaboration with the University of Idaho will result in testing electrical geophysical techniques.

A7.3 University Place Site

The soil profile of the University Place site in Idaho Falls, Idaho, consists of approximately 5 to 10 m of dune sand overlying a fractured basalt surface. Preliminary evaluation of ground-penetrating radar at this site appears to be able to detect the basalt surface.

A7.4 Jefferson Canal Site

The Jefferson canal site is located near Mud Lake, Idaho. The site consists of an approximately a section of land within which four individual research sites have been identified. This site was chosen to incorporate a variety of topography and surface soil conditions. The subsurface structure exhibits more than 100 ft of Lake Tarenton sediments. Three boreholes have been drilled to a depth of 50 ft to evaluate borehole-to-borehole radar tomography. Preliminary results indicate a layered system of sands to silts and clays. Infiltration studies will be conducted at the Jefferson Canal site to evaluate the incorporation of geophysical interpretation into vadose zone transport numerical models.

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Appendix B

Vadose Zone Investigations Conducted at Idaho National Engineering and Environmental Facilities

Appendix B

Vadose Zone Investigations Conducted at Idaho National Engineering and Environmental Facilities

The purpose of this section is to establish a knowledge base of vadose zone activities for the Idaho National Engineering and Environmental Laboratory (INEEL) and document the path that has led to the current state of vadose zone programs at. The historical perspective will support efforts to define a framework for planning and integrating vadose zone activities at the INEEL. Though historical vadose zone investigations at the INEEL were not conducted within an integrated program, each investigation was conducted to achieve specific goals. It is not the intent of this document to reproduce detailed technical summaries of INEEL vadose zone sites that can be found elsewhere. A list of bibliographic references is available at the INEEL Vadose Zone Science and Technology Program Office.

B1. RADIOACTIVE WASTE MANAGEMENT COMPLEX

The Radioactive Waste Management Complex (RWMC) is located in the southwest portion of the INEEL and covers approximately 144 acres. An aerial view of the RWMC is provided in Figure B-1. The facility is divided into two components: (1) The Subsurface Disposal Area (SDA) and (2) The Transuranic Storage Area (TSA). The SDA covers about 88 acres, and has been used for the disposal of radioactive and hazardous waste since 1952. The TSA has been used for the aboveground storage of transuranic waste since the 1970s. Other projects at the RWMC include investigations of shallow land burial technology, waste retrieval and processing, and the interim storage and treatment of transuranic waste until transport to a permanent federal repository.

Figure B-1. Aerial view of the Radioactive Waste Management Complex.

Prior to 1970, waste was placed in unlined pits and trenches within the 5 to 20-ft-thick surficial sediments of the SDA. From 1954 to 1970, organic and radioactive waste was received from the Rocky Flats Plant in Colorado. The waste included organic solvents, low- and high-level radioactive liquids (including transuranic elements), oils, and contaminated clothing. Before transport to the RWMC, solvent waste was mixed with calcium silicate to create a semi-solid, grease-like compound. Over time, waste containers developed leaks, freeing waste to migrate through the underlying soils and sediments. Organic vapors, primarily carbon tetrachloride, have been found in the soils and sediments beneath the SDA, through the 580-ft-thick vadose zone and in the groundwater beneath the site. Infiltration of rainwater and snowmelt may have increased the mobility of organic and radioactive contaminants into the vadose zone beneath the SDA. Past floods within the disposal pits at the SDA may have contributed to the migration of contaminants beneath the facility.

B1.1 Summary of Previous and Ongoing Vadose Zone Research

Moisture monitoring at the SDA was conducted in 1985 through 1989 and 1993 through 1995. The neutron probe was used to monitor moisture changes in two holes through 1993. In 1994 and 1995, the network was expanded to include 24 neutron access tubes scattered throughout the SDA. All tubes were installed through the surficial sediments to the basalt interface. Infiltration and drainage from the sediment to the basalt were calculated. Analysis of the data indicated that most of the water that infiltrates into the soil is provided by the spring snowmelt (though heavy spring and summer rainfall can contribute water for infiltration). Results indicated that infiltration was sensitive to the snowmelt process with snowmelt occurring over frozen ground providing the greatest opportunity for ponding of water and then deep infiltration when the ground thaws. The monitoring also found that the most significant drainage of water to the basalt occurred in locations where ponding occurred.

Perched water level monitoring was conducted using existing wells from 1992 through 1994 to evaluate the presence of perched water and to estimate travel times for the wetting front. Perched water was measured at the surficial sediment/basalt interface and above the 110-ft interbed (also referred to as the B-C interbed) and the 240-ft interbed (also referred to as the C-D interbed). Perched water has existed at some of these sites for decades. The data suggest that recharge events generally occur in response to infiltration of spring snowmelt or precipitation. The wetting front travel times are in the order of days from land surface to basalt and tens of feet per month to the 110- and 240-ft depths. Data also suggest that water recharged at the spreading areas to the west of the RWMC could impact perched water under the SDA.

B1.2 Organic Contamination in the Vadose Zone

Within the SDA are individual storage and disposal areas consisting of pits, trenches, aboveground storage pads, and soil vaults. Organic contamination in the vadose zone (OCVZ) is defined as that part of the vadose zone that is potentially contaminated by volatile organic compounds (VOCs) beneath and adjacent to the SDA of the RWMC. The presence of organic contaminants in the vadose zone beneath the RWMC is the result of burial and subsequent breach of containerized organic waste. The vadose zone has become contaminated with VOCs and trace levels (low parts per billion) of carbon tetrachloride have been detected in the underlying SRPA. Vapor vacuum extraction (VVE) has been selected as the preferred alternative for cleanup of the OCVZ. To implement the selected remedy, five new extraction wells and 10 monitoring wells were installed in or adjacent to the SDA of the RWMC during 1994. In addition to the new wells, one extraction and five monitoring wells previously installed for the OCVZ treatability study conducted in 1993 (Chatwin et al. 1992) were incorporated for extracting and monitoring VOCs. All of these well were completed above the 110-ft (i.e., B-C) interbed or 240-ft (i.e., C-D) interbed.

Through mid-year 2000, a total of 35,280 kg of solvents had been recovered. Carbon tetrachloride is the largest contributor to the VOC mass removed accounting for 65% of the total. The spatial and temporal distribution of VOCs show an overall decrease in the areal extent of the VOC plume since the start of operations in January 1996 and a decrease in the carbon tetrachloride concentration at the center of the plume.

B1.3 Modeling

Numerous modeling studies of the vadose zone have been conducted at the RWMC. These studies fall into two primary categories: simulation of water movement and simulation of contaminant movement. Over time, the emphasis of these modeling studies has shifted slightly from hypothesis and assumptions to a greater inclusion of site-specific data on water movement and contaminant transport.

Modeling of VOCs has been the most successful in emulating the physical system. Predictive simulations have been partially validated by subsequent sampling. Adequate confidence in the VOC modeling results has allowed the VOC modeling to be used to direct operation and revision of the subsurface VVE remediation system. The dissolved-phase transport simulation studies have been less successful, primarily because of inadequate field observations of water movement and dissolved-phase contaminant movement in the vadose zone. However, this inability to conclusively demonstrate model calibration led to expanded characterization activities that are in progress at the RWMC to improve the vadose zone monitoring network.

B1.4 Current Vadose Zone Monitoring Capabilities

Of the 41 lysimeters that have been installed in the surficial sediments in and near the SDA beginning in 1985, approximately 30 are still functional (i.e., will still hold a vacuum). Of these 30, approximately 14 have yielded a water sample in the last 2 years of monitoring. These 14 lysimeters are from 12 different locations because some of the lysimeters are at different elevations at the same location. In addition, seven suction lysimeters were installed as part of the Subsurface Investigations Program at depths from 32 to 227 ft beneath the SDA. These deeper lysimeters are installed primarily in sedimentary interbeds. However, one lysimeter was installed in a fractured basalt region at a depth of 88 ft. This lysimeter still functions and consistently yields water volumes on the order of 500 to 1,000 ml for each sampling event. There are 26 neutron access tubes (NATs) at the SDA. Two NATs were installed in 1986 as part of the Subsurface Investigation Program. The NAT network was expanded to 19 locations in 1994. Three NATs have been added since 1994. In addition, three NATs were installed by the U.S. Geological Survey (USGS). Of the 26 NATs, eight have shown ephemeral perched water that develops in response to snowmelt and summer rain showers.

As part of the development of the advanced tensiometer, long-term research initiative funding was used to create a test installation of a series of deep tensiometers in one well at the SDA. These tensiometers indicated that the basalt matrix was considerably wetter than previously thought. Moisture movement has been documented from land surface to 38 ft below land surface at this well in an average water year.

In addition to suction lysimeters and NATs, a network of deep wells is used for monitoring perched water. Of the approximately 90 wells that have been drilled to the 110-ft interbed (i.e., B-C interbed), 14 have shown indications of perched water at this depth. Of these, three have been completed for monitoring perched water levels and recovering water samples for contaminant analyses. During the last 3 years of monitoring, no water samples have been recovered during quarterly sampling. Of the approximately 40 wells drilled to the 240-ft interbed (i.e., C-D interbed), 11 have shown indications of saturated conditions. Of these 11, three have been completed for perched water level monitoring and recovery of water samples. Of these three wells, only one has consistently yielded water samples. The well consistently yielding samples was the first water well installed in the SDA and was constructed in 1972. No perched water level measurements have been conducted since 1995.

The variability of the suction lysimeters, NATs, and perched water wells in yielding water samples, both spatially and temporally, points to the variability in water movement in a complex hydrological regime beneath the SDA. Preferential movement of water is occurring intermixed with regions where it is not occurring. Some hypothesis can be made to explain observed water behavior. In Well 77-2, for example, which had perched water before 1992 but not since, the addition of soil to the pit surface as part of recontouring efforts in the late 1980s may have proved effective. The water that formerly infiltrated and caused perched water at Well 77-2 is now running off the sloped surface of the pit and infiltrating somewhere else.

During 1999 and 2000, an expansion of the vadose zone monitoring network occurred. Fourteen wells were drilled inside the RWMC facilities fence, and nine wells were drilled outside the fence. Of the inside wells, five were drilled to the bottom of the 110-ft (i.e., B-C) interbed and were instrumented with tensiometers and suction lysimeters within the interbed, and five were drilled to the bottom of the 240-ft (i.e., C-D) interbed and were instrumented within the interbed. The remaining four wells were drilled for the OCVZ project for extraction capabilities. Two of these OCVZ wells were drilled to just above the 110-ft interbed. One was drilled to a depth of 435 ft, and one was drilled into the aquifer. The latter well also was completed for monitoring in the aquifer. Of the nine outside wells, one was drilled to the 110-ft interbed and instrumented with tensiometers and suction lysimeters within the interbed, one was drilled to the 240-ft interbed and instrumented within the interbed, and five were drilled to the 240-ft interbed and instrumented within both the 110-ft and 240-ft interbeds. The other two wells were drilled to the aquifer and completed as aquifer monitoring wells. In addition to expanding the ability to recover water samples from the deeper vadose zone within the SDA, the other objectives of this drilling effort are to improve understanding of spatial variations of hydrologic properties of the interbeds, to monitor the potential influence of the spreading areas in the vadose zone close to the SDA, and to better bound the extent of VOC contamination in the aquifer.

Two additional expansions to the vadose zone monitoring network are planned for 2001. The first consists of additional monitoring wells for the OCVZ project. Four wells will be drilled to the 240-ft interbed and will be completed with gas ports and extraction intervals, and five vadose zone wells with similar capabilities will be drilled to interim depths beneath the 240-ft interbed but above the water table. These nine wells all will be either inside the RWMC facility fence or immediately adjacent to it and will provide additional VOC monitoring and extraction capability. In addition to the vadose zone wells, 10 aquifer monitoring wells will be drilled at various distances outside the facility fence. The aquifer wells are designed to better bound the extent of contamination in the aquifer and to assess the influence of a low-permeability region to the south-southwest of the RWMC.

The second expansion in vadose zone monitoring capabilities consists of monitoring instrumentation that will be emplaced using direct push technology within and immediately beneath the waste zone in selected SDA pits. The instrumentation will consist of tensiometers, suction lysimeters, soil moisture probes, gas ports, and probes to assess oxidation-reduction, pH, and temperature. In addition, clear plastic probes also will be installed to allow visual access. The objective of the second expansion activity is to assess waste zone hydrology and geochemistry in the vicinity of targeted waste streams to improve the basis for making source release simulations that are used in predicting contaminant flow and transport.

B1.5 Deficiencies in Vadose Zone Understanding

- Funding to allow vadose zone monitoring for a sufficient length of time. Monitoring must be continued for a long enough duration to collect data from several very wet years, very dry years, and the range of conditions between the extremes. The resultant data will provide the variation in conditions that can lead to a through understanding of vadose zone processes. Without this information, vadose processes cannot be thoroughly described. The resultant understanding of vadose zone processes is a vital component to understanding impacts to the environment when radioactive waste is buried in soil pits and trenches.

- A paucity of contaminant monitoring data is available from the vadose zone.

- The monitoring of the expanded moisture monitoring network was discontinued before a "wetter than average" year occurred resulting in the failure to identify all or maybe even most of the potential variables that influence infiltration.

- The number and distribution of the monitoring points are limited, and no method exists for accurately quantifying the areal and vertical distribution of infiltration.

- The spatial distribution of monitoring points requires evaluation.

- Perched water level monitoring must be conducted over timeframes representative of temporal infiltration events.

- Lateral flow in the vadose zone for the spreading areas has not been adequately evaluated.

- The distribution of hydraulic conductivity within the sedimentary interbeds is poorly defined.

- The application of geophysical (either surface or borehole) methods is limited.

- No method is available for locating, measuring, and monitoring fast flow patterns in the subsurface.

- Fracture flow in basalts is assumed to be very fast in vadose zone models. This assumption must be tested against field data.

- Moisture release curves for various basalt textures and sedimentary layers are limited to a small number of samples.

- Homogeneous and isotropic conditions are assumed in numerical models. Such conditions are inappropriate at the scale needed for remediation of single trenches.

B2. IDAHO NUCLEAR TECHNOLOGY AND ENGINEERING CENTER

The Idaho Nuclear Technology and Engineering Center (INTEC) lies on 210 acres in the southwestern portion of the INEEL, just north of the Central Facilities Area (CFA). An aerial view of the INTEC is provided in Figure B-2. The facility began operations in 1952, with its primary purpose being to recover highly enriched uranium from spent nuclear fuel (SNF). This process created highly radioactive liquid waste. The waste was initially stored in underground storage tanks (i.e., the Tank Farm) before calcining (a process that recasts the liquids into a solid, more stable form). Another component of the liquid waste stored at the Tank Farm is sodium. To date, the tanks have not leaked. However, transfer lines that carried the radioactive liquids to the tanks have leaked and contaminated the surficial sediments and soils in several locations at the INTEC. In 1992, the U.S. Department of Energy (DOE) announced that fuel reprocessing at the INTEC would be phased out. The current mission for the INTEC is the management and interim storage of spent nuclear fuel and treatment and interim storage of radioactive waste for future disposal.

Figure B-2. Aerial view of the Idaho Nuclear Technology and Engineering Center.

Other low-level liquid waste was disposed of in a deep injection well at the INTEC from 1952 to 1989. This practice has created groundwater contamination with several radionuclides above the maximum contaminant level (MCL) set by the U.S. Environmental Protection Agency (EPA). These contaminants include ^{3}H, ^{90}Sr, and ^{129}I. At least twice during this operation, the disposal well's casing developed leaks that provided a conduit for the injection of radioactive liquids into the vadose zone.

Additional sources for vadose zone contamination include percolation ponds, leaky storage tanks, pipes, inadvertent spills, and migration of precipitation or irrigation water through contaminated soils.

B2.1 Perched Water Below INTEC

Two perched water zones are located under the facility at approximately 110 and 380 ft below ground surface (bgs). Uncertainty exists about the degree of connection between the perched water in the northern portions of the INTEC and that in the south. Water quality monitoring has shown that the shallow perched water contains localized areas of elevated ^{90}Sr concentrations.

The Big Lost River intermittently flows to the northwest of the INTEC facility. The river flows over a thick alluvial sequence, which promotes water loss along its entire reach. In the late 1980s and early 1990s, the Big Lost rarely flowed, but beginning in 1996, flow in the river has been nearly continuous.

B2.2 Summary of Previous and Ongoing Vadose Zone Studies

The OU 3-13 comprehensive remedial investigation phase of the remedial investigation/feasibility study (RI/FS) (Rodriguez et al. 1997; DOE-ID 1997) presented the available data for Waste Area Group (WAG) 3 concerning site conditions and the nature and extent of contamination. The remedial investigation examined 92 of the 94 designated release sites and the INTEC windblown area. The sites evaluated were (1) carried forward to the feasibility study, (2) determined to require no further action based on assessment in the remedial investigation/baseline risk assessment (RI/BRA), Track 1 or 2 investigations, or the Federal Facilities Agreement and Consent Order (FFA/CO) (DOE-ID 1991), or (3) determined to be addressed under other programs that satisfy Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (42 USC § 9601 et seq.) requirements.

Several investigations of the vadose zone are planned for the INTEC. One of the investigations will focus on the Tank Farm soil but also will include other INTEC areas near the Tank Farm. This investigation is part of the WAG 3 Operable Unit (OU) 3-14 RI/FS inquiry (DOE-ID 2000a), which was established in the OU 3-13 Record of Decision (ROD). The WAG 3 OU 3-13 post-ROD groundwater monitoring will mount another evaluation to monitor remedial actions. The scope of the OU 3-13 remedial action evaluation focuses on INTEC perched water and water quality issues.

The OU 3-14 RI/FS subsurface investigation (DOE-ID 2000a) will involve a phased approach conducted over several years. Phase I will include a surface gamma survey performed over the entire Tank Farm. It will also include a gamma logging survey of the existing moisture probes and monitoring wells at the Tank Farm. Phase I will involve the installation of 120 closed probehole casings into the Tank Farm soil. These probes will be placed based on location grids in the known contamination areas and a standard equilateral grid to cover the entire Tank Farm. These probeholes will be logged using a gamma radiation detection tool to map the presence of subsurface radiological contamination in the vadose zone to 45 ft bgs (DOE-ID 2000c).

Phase I also will involve the coring of the INTEC injection well to the total depth. Two monitoring wells (one adjacent to the injection well and one downgradient) also will be cored before reaming and well construction. These cores will be given to the OU 3-13 project for use in analyzing the vadose and groundwater regimes (DOE-ID 2000b).

Phase II will involve the installation of several larger diameter probeholes in Tank Farm soil. These probeholes will be larger and, therefore, able to accept a larger more complex logging tool that will be able to refine and speciate the radionuclides present in the soil. This size of casing also will accommodate the use of active tools for the detection of alpha emitting radionuclides. Location of the probeholes will be based on data collected in Phase I.

Phase II also will involve the installation of several sets of moisture monitoring tubes and discrete soil sampling. Lysimeters and tensiometers also will be installed at these sites. There will be approximately eight locations both inside and outside the Tank Farm. These moisture monitoring stations will be used to monitor moisture and contaminant movement in the vadose zone.

The OU 3-13 investigation will focus on water quality issues and monitoring the perched water levels. Part of the investigation includes drilling 15 new wells: four to the base of the surface alluvium, five to the shallow perched water zones (110 to 140 ft bgs), five to the deep perched water zone (380 to 400 ft bgs), and one to the Snake River Plain Aquifer. The perched water zones are expected to drain following implementation of the WAG 3 ROD remedial action activities (DOE-ID 1999). The Tank Farm interim action activity includes covering the Tank Farm with a second liner, lining drainage ditches, and redirecting building drainage, all to restrict infiltration into the Tank Farm subsurface. The OU 3-13 perched water remedial action is the relocation of the percolation ponds to a site far enough removed from the INTEC facility to prevent infiltration from the ponds recharging INTEC perched water. This remedial action will be monitored for a period of 5 years to evaluated whether additional recharge controls are necessary to meet the remedial action goal of drying up the perched water zones. During this period, stable isotope and vadose zone tracer studies also will be performed to evaluate perched water sources.

B2.3 INTEC Modeling

The INTEC vadose zone modeling deficiencies are described in Section 2.3.1 below. The text has been obtained in its entirely from the 1999 Draft OU 3-14 RI/FS Work Plan, Revision 2 (Hull et al. 1999). A full discussion of the modeling is in Appendix C. The problems discussed for the INTEC vadose zone modeling are frequently similar to the problems encountered at most areas of the INEEL.

The TETRAD code was used for the OU 3-13 subsurface pathway flow and transport modeling (Becker et al. 1998). The TETRAD is a powerful code and the OU 3-13 simulation results have been accepted by the U.S. Department of Energy, Idaho Operations Office (DOE-ID), EPA, and the Idaho Department of Health and Welfare (IDHW). A substantial effort has been expended to create a model of the INTEC with the TETRAD code that will directly support the OU 3-14 RI/BRA and the OU 3-13 remedial action evaluations.

2.3.1 OU 3-13 RI/BRA Model Uncertainty

The level of uncertainty in the OU 3-13 RI/BRA was not acceptable, resulting in the creation of OU 3-14, focusing on contaminant transport from the Tank Farm. The following subsections describe the primary issues in the OU 3-13 RI/BRA that will be addressed in the OU 3-14 RI/BRA model.

2.3.1.1 Overprediction of Plutonium and Sr-90 in Perched Water. The OU 3-13 RI/BRA (Rodriguez et al. 1997) vadose zone model predicted easily detectable concentrations (greater than 100 pCi/L) of plutonium and high concentrations of Sr-90 in the upper interbed (approximately 130 ft bgs) by the 1990s. These concentrations were predicted to exist over much of the Tank Farm area. However, plutonium has not been measured in the limited number of analyses of perched water from the upper interbeds and though large Sr-90 concentrations have been found, they are in relatively isolated portions of the INTEC compared with the model predictions. Possible reasons for the discrepancies between the field data and model predictions are listed below:

- Less plutonium and Sr-90 was released than estimated in the OU 3-13 RI/BRA

- Plutonium and Sr-90 are sorbed in the Tank Farm alluvium; whereas in the OU 3-13 RI/BRA model, the hypothesis was made that sorption does not occur in the Tank Farm sediments

- Plutonium and Sr-90 are sorbed in the fracture sediment coatings and infill in the fractured basalt whereas in the OU 3-13 RI/BRA model, the hypothesis was made that sorption does not occur in the fractured basalt.

These potential explanations should be tested through a field characterization and monitoring activity with particular emphasis placed on plutonium inventory and mobility.

2.3.1.2 Uncertainty In Vadose Zone Transport Calibration. In the OU 3-13 RI/BRA modeling, a significant amount of both hydraulic and contaminant transport information was available for calibration of the aquifer model. However, very little information was available for calibration of the vadose zone model. Therefore aquifer contaminant flow and transport predictions have relatively little uncertainty while the vadose zone flow and transport uncertainty is large.

The OU 3-13 RI/BRA vadose zone model was calibrated to chloride concentrations from Percolation Pond disposals in wells immediately surrounding the Percolation Ponds. The chloride concentrations in these wells is dominated by disposal of pond water. The calibration was, therefore, relatively insensitive to hydrologic and transport properties in the vadose zone. The model was not calibrated to chloride concentrations in more distant wells, which could have given some spatial variation for testing the calibration. Measurements of transport in the vadose zone are required that can be directly tied to the Tank Farm contaminant sources.

2.3.1.3 Uncertainty in Vadose Zone Dispersivity. The predicted peak aquifer contaminant concentration resulting from transport of contaminants through the vadose zone are generally controlled by advective transport. However, dispersive transport can be the dominant transport mechanism for certain radionuclides in certain environments. Transport of Sr-90 from Tank Farm through the vadose zone to the underlying aquifer is one of those cases.

Dispersion is not a well-quantified transport mechanism but rather a factor used to represent many transport mechanisms that are not incorporated into the model. Predicted peak Sr-90 concentrations in the aquifer are extremely sensitive to the dispersion in the vadose zone and the dispersion in the vadose zone is highly uncertain. Therefore, the Sr-90 model sensitivity to dispersion will be quantified in the OU 3-14 investigation. This section summarizes the dispersion transport mechanism and the effects on Sr-90 model predictions.

The use of large time steps along with large grid blocks leads to significant numerical dispersion. Though TETRAD has simulation options for dispersion control such as higher order solutions, so far the simulations have been too numerically cumbersome to include those controls. As a result, the magnitude of dispersion in the simulations is unknown but is substantially greater than the assigned values. For simulation problems dominated by dispersive transport, such as Sr-90 transport from the perched water down to the aquifer, the consequence is substantial uncertainty in the simulation results.

Figure B-3 illustrates the effect of dispersion on transport. The first diagram in Figure B-3 illustrates migration of a conservative contaminant in the absence of dispersion. An initial pulse of contaminant released near the ground surface at time 0 (t=0) migrates downward to the aquifer along with the ambient recharge. In the absence of dispersion, the peak concentration stays the same and the width of the peak (the depth interval over which it spreads) remains constant. The contaminant peak reaches the aquifer at some time in the future dependent only on the rate of downward migration in the vadose zone.

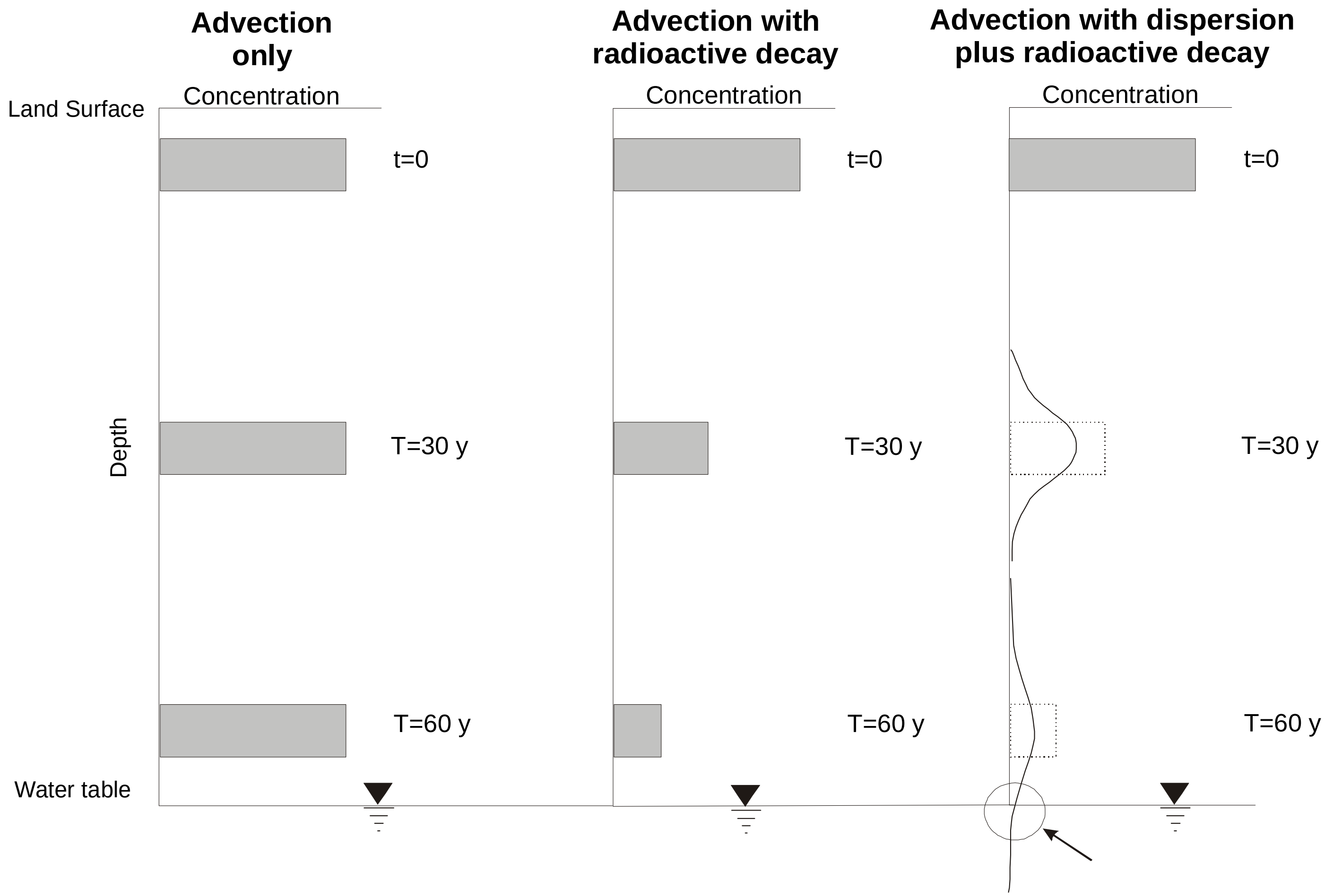

Figure B-3. Graphical depiction of the effects of dispersion on a contaminant plume.

The second diagram illustrates the effect of adding radioactive decay to advection. The total activity released at time 0 begins to decay. For a radioactive contaminant with a half-life of 30 years, one-half of the original activity decays in 30 years. As the contaminant peak moves down through the vadose zone, the concentration decreases with time. In Figure B-3, for a contaminant with a half-life of 30 years and a residence time in the vadose zone of 70 years, the peak concentration is about 20% of the original concentration of the release. Under the conditions encountered at the INTEC, Sr-90, with a half-life of 29 years and a residence time in the vadose zone of about 300 years, decays to less than 0.1% of the original activity before the peak reaches the aquifer.

The third diagram in Figure B-3 illustrates the effect of dispersion on migration through the vadose zone. With dispersion, not all of the contaminant moves at the same rate through the vadose zone. Some of the contaminant moves a little faster than the average velocity, and some moves a little slower. The activity of the contaminant remains the same, but because the contaminant spreads out over a larger area of the vadose zone, the peak concentration is reduced. Some of the contaminant moves faster than the bulk of the peak; therefore, it will reach the aquifer sooner than the peak reaches the aquifer under advection alone.

In the simulation used for the OU 3-13 RI/BRA (Rodriguez et al. 1997), the Sr-90 residence time in the vadose zone was sufficiently long to result in the decay of almost all of the Sr-90 before the surface releases could reach the aquifer. However, some of the Sr-90, traveling faster than the average velocity of the peak, reached the aquifer sooner. The shorter residence time resulted in less time for radioactive decay and, therefore, resulted in a higher exposure concentration in the aquifer.

Dispersion in the simulated Sr-90 concentration comes from two sources. One is a mechanical dispersion coefficient used in the code to mimic the natural spreading of a contaminant as it migrates through heterogeneous systems. A value of 5 m was assigned in the OU 3-13 RI/BRA modeling for this dispersivity based on the results of the large-scale infiltration test (Magnuson 1995). A large amount of uncertainty is associated with this value, especially in the case of Sr-90 migration through the vadose zone in the area of the INTEC. The second source is numerical dispersion that results from the numerical approximation to the governing equations. This second source of dispersion is an artifact of the code and does not represent a natural process. Because the OU 3-13 RI/BRA vadose zone model was not calibrated to a breakthrough curve from field data, the amount of dispersion that occurs in the natural system is unknown. Therefore, whether the dispersion observed in the simulated Sr-90 concentrations reflects the natural system cannot be determined. Dispersion is the most important process controlling the exposure concentration of Sr-90 in the aquifer, and the amount of dispersion generated by the model is uncalibrated to the natural system.

Field measurements should be obtained that are representative of Sr-90 transport in the vadose zone that can be attributed to releases into the Tank Farm soils. These measurements would be used to calibrate the vadose zone transport model. Ideally, the measurements would be taken over time at several locations to determine transient changes in Sr-90 concentrations. For the purposes of the OU 3-14 RI/FS, insufficient time is available for the determination of trends. Rather, single-point measurements or measurements over a short time period must suffice. They will at least provide an order of magnitude bound for what the simulator should be predicting. Continued monitoring will provide information to verify or disprove the model predictions. This continued monitoring is very important because portions of the Tank Farm will continue to operate. When the Tank Farm is inoperable and remediation actions begin, the data will provide the information needed to choose an appropriate closure plan of action.

2.3.1.4 Summary of Model Uncertainty and Data Needs. The level of uncertainty in the OU 3-13 RI/BRA was not acceptable, resulting in the creation of OU 3-14, focusing on contaminant transport from the Tank Farm. The key vadose zone and site conceptual model uncertainties are the following:

- The assumption that contaminated Tank Farm soils are the source of contamination was not tested through a field characterization and monitoring activity in the vicinity of the Tank Farm. If the field characterization and monitoring activities indicate that a source of contamination other than the Tank Farm exists, then additional characterization will be required to identify the source.
- Uncertainty about the source of perched water contamination.
- Uncertainty of the vadose zone stratigraphy including interbed thickness and continuity.
- Assumption of homogenous interbed hydraulic properties.
- Basalt hydraulic conductivity anisotropy ratio.

The primary issues in the OU 3-13 RI/BRA are the following:

- Limited size of numerical model domain
- Overprediction of plutonium and Sr-90 in perched water
- Uncertainty in vadose zone transport calibration
- Uncertainty in vadose zone dispersivity.

The following is a list of areas in which field data and numerical model sensitivity analysis is needed to resolve the OU 3-13 RI/BRA model uncertainty issues:

- Perched water contaminant characterization in the vicinity of the Tank Farm to show that the high Sr-90 concentrations in the perched water result from the Tank Farm contamination sources.
- Regular monitoring of perched water wells to establish concentration trends in contaminants and geochemistry. Monitoring must be continued long term to develop the trends.
- Model sensitivity analysis to quantify the sensitivity of predicted peak Sr-90 concentrations in the aquifer to the vadose zone dispersion.

2.3.2 Lack of Moisture Monitoring in Vadose Zone Interbeds

Monitoring wells, with and without standing perched water, are located in the vicinity (but not within the boundary) of the Tank Farm. The data from the wells have been interpreted in several ways. Two primary interpretations include (1) that two distinct perched water bodies are located at the 110 to 150-ft depth (one in the northern part and one in the southern part of the INTEC) and (2) that numerous small discontinuous perched water bodies are present. The hypothesis used in the OU 3-13 RI/BRA modeling was that the sedimentary interbeds were wet (greater than 90% saturated) everywhere with some locations only a little wetter than others. The simulation model was parameterized so that the minimum simulated moisture saturation in the sedimentary interbeds was approximately 90%. Depending on the slope and elevation of the interbeds and local water fluxes, the simulated soil moisture content in the interbeds was either slightly below saturation or had a small amount of perched water.

Currently, no wells are located directly beneath the Tank Farm to indicate the presence of perched water. Monitoring of the interbed moisture contents beneath and in the vicinity of the Tank Farm is required to evaluate the above-described hypothesis used in the OU 3-13 RI/BRA model and to provide a basis for calibration of the OU 3-14 RI/BRA numerical model. The OU 3-13 conceptual model could require revising if small-scale heterogeneity in the interbed properties causes very localized perched water to develop and the areas without perched water are much drier than assumed in the model. These same heterogeneities in the interbed soil properties also could significantly affect the simulated transport.

2.3.3 Conceptual Model

In the OU 3-13 RI/BRA simulations (Rodriguez et al. 1997), the high contaminant concentration levels (in particular, Sr-90) that are found in perched water wells in the northern half of the INTEC were hypothesized to have resulted from the leaching of contaminants from Tank Farm sediments. This hypothesis was made without the support of direct continuous field evidence because no perched water wells monitor the perched water directly beneath the Tank Farm. The OU 3-14 RI/BRA model also is structured using the hypothesis that the Tank Farm contaminated soils are causing the elevated perched water contamination.

A complex layering of basalt flows and sedimentary interbeds characterize the subsurface of the INTEC. Wells drilled to a depth of 700 ft have encountered 23 basalt flow groups and 15 to 20 sedimentary interbeds. The most significant unresolved stratigraphic issue in the OU 3-13 RI/BRA (Rodriguez et al. 1997) is how the incorporation of stratigraphic data into the OU 3-13 RI/BRA model affected the model predictions.

B2.4 Current Vadose Zone Monitoring Capabilities

There are 45 piezometers in place in the perched water below the INTEC. Some of the piezometers are nested and have transducers in them. A few NATs are in the Tank Farm Area. Neither the piezometers nor the neutron tubes are being monitored, though OU 3-13 remedial actions are planned to begin in the fall of 2000 and will include monitoring of the vadose zone network.

B2.5 Deficiencies in Vadose Zone Understanding

- The Big Lost River is a significant source of INTEC perched water recharge, yet data have not been collected to quantify this source term. If flow in the river stops for the time period during which the INTEC and Tank Farm investigations occur, the impact of flow in the river on perched water formation and recharge will be difficult to access. A long-term program of characterization monitoring is required to quantify infiltration.

- Drilling site locations have been established by feasibility (e.g., locations where few underground structures existed) rather than technical issues. Therefore, sample collection is based on opportunity rather than statistical justification. This may result in the collection of a skewed sample set. A statistical, stochastic analysis should be conducted to determine whether present monitoring locations are sufficient.

- Monitoring and sampling have not been continued long enough to collect a statistically significant amount of data to characterize the site and represent the full range of precipitation (see Section 3.1.2.1 of this document).

- Placing a second cover over the Tank Farm may prohibit collection of data that are representative of past infiltration. In addition, drilling activities associated with the OU 3-14 investigation may tear or disturb the new cover permitting water to move through it. The second cover also may enhance the subsurface moisture content, less evapotranspiration, and, thereby, influence migration and moisture measurements.

- Instrumentation that can be accurately calibrated and employed in a gravel vadose zone is not developed.

- Perched water level data collected from wells around the Tank Farm show a pronounced effect from changes in barometric pressure. This limits the usefulness of the small changes in water level data to determine any sources of water. Techniques are not developed to measure accurately long-term trending of water levels.

- Steam disposal drains are not monitored. Localized recharge resulting from this practice is not quantified and are the effects unknown.

B3. CENTRAL FACILITIES AREA

The Central Facilities Area (CFA) is located in the south-central portion of the INEEL, approximately 93 km (50 mi) west of Idaho Falls, Idaho (see Figure B-4). The original facilities at the CFA were built in the 1940s to house U.S. Navy gunnery range personnel. The facilities have been modified over the years to fit the changing needs of the INEEL and now provide craft, office, service, and laboratory space.

Figure B-4. Aerial view of the Central Facilities Area.

The CFA vadose zone contamination issues concern the leaching (1) of landfill waste from three landfills, (2) of mercury, nitrate, and other metals from a dry pond, and (3) of nitrate from the former sewage plant drainfield. Another concern is infiltration through landfill covers and performance of the covers.

During the process of renewing the Wastewater Land Application Permit (WLAP) for the sewage treatment facility at the CFA and completing the Operable Unit (OU) 4-12 Post-Record of Decision monitoring program, nitrate concentrations in wells (CFA-MON-A-002 and CFA-MON-A-003) exceeded the EPA MCL of 10 mg/L. Concerns about the potential source of elevated nitrate in the CFA monitoring wells were subsequently raised. An evaluation in progress of possible sources indicates that the former sewage treatment plant (CFA-08) was the most probable source.

The CFA Landfills I, II, and III are located approximately 0.8 km (0.5 mi) north of the CFA proper. The predominant waste types disposed of in the landfills were construction, office, and cafeteria waste. Lesser amounts of potentially hazardous waste, including waste oil, solvents, chemicals, and paint also entered the landfills. The Record of Decision for the landfills required monitoring of the vadose zone overlying the Snake River Plain Aquifer (SRPA) at all three landfills, and monitoring of water infiltration into the soil covers placed over the landfills (DOE-ID 1995).

The CFA Experimental Calcining Waste Pond (CFA-04) site consists of a shallow pond formerly used for the disposal of waste from operations at CFA-674. Currently, CFA-674 is not discharged to the Waste Pond. Three waste generation processes were identified as sources of contamination: (1) 1953 to 1965, mercury-contaminated waste from the calcine development work in CFA-674; (2) 1953 to 1969, liquid laboratory effluent from the Chemical Engineering Laboratory; and, (3) dates unknown, bulk waste including asbestos-containing roofing material from construction projects at the INEEL.

Liquid and solid waste resulting from operations at the Chemical Engineering Laboratory and discharged to the pond may have included simulated calcine, sodium nitrate, nitric acid, tributyl phosphate, uranyl nitrate, high grade kerosene, aluminum nitrate, hydrochloric and chromic acid, di-chromate solutions, terphenyls, heating oil, zirconium, hydrofluoric acid, trichlorethylene, and acetone.

B3.1 Summary of Previous and Ongoing Vadose Zone Studies

Infiltration monitoring has been conducted at the CFA landfills to determine whether precipitation infiltrated through the soil covers and percolated through the buried waste, possibly picking up contamination and carrying it to the aquifer. The time-domain reflectrometry (TDR) and neutron probe data indicate that all or most of the recharge occurs in April and May and coincides with the spring snowmelt event. Neutron probe data also suggest that recharge is sporadic and depends on the amount of precipitation that falls in the winter, the snowpack size, and the rapidness of the spring thaw (LMITCO 1999).

Soil-gas monitoring was conducted at the CFA landfills to evaluate production and migration of contaminated soil gases. Soil gas samples were collected and analyzed from approximately 11 to 107 ft bgs. Nine contaminants were detected including four constituents that are typically contained in solvents and degreasers, two that are degradation products of solvents, two that are freons, and one that is generated by waste degradation. Soil-gas contaminants have reached the deepest soil gas sampling ports at depths of 94 to 107.5 ft. The organic vapors, primarily chlorinated solvents, are probably migrating through preferential vertical and horizontal flow paths in the fractured basalt. The total depth the contaminants have reached is unknown, but groundwater does not appear to be impacted at the present time.

Sampling activities at the CFA-04 dry pond indicated that the surface and subsurface soil are contaminated with low levels of arsenic, Cs-137, U-234, U-235, and U-238 above background concentrations. Mercury was found at concentrations up to 650 mg/kg. A time critical removal action was initiated in 1994 to remove mercury contamination in the pond. Approximately 3,066 yd^3 of mercury contaminated soil were removed from the ground including calcine, soil contaminated with calcine, and soil contaminated with mercury from effluent discharges to the pond. A small amount of asbestos also was removed from the pond bottom during removal action activities. Nonfriable asbestos and roofing material were not disturbed and remained buried in the pond berm.

B3.2 Vadose Zone Modeling

Modeling of infiltration at the CFA landfills was conducted using the HELP model (Sorenson 1996) and nitrate migration modeling was conducted at three sites using GWSCREEN (Bukowski et al. 1999). The infiltration modeling at the CFA landfills using the HELP model was done for cover design purposes and the nitrate migration modeling (GWSCREEN) was done to determine the most probable site as a source of nitrate found in the CFA facility monitoring wells.

The GWSCREEN modeling was performed at three potential nitrate source sites in the CFA area including the new sewage treatment plant (STP), the old sewage treatment plant (CFA-08), and the dry pond (CFA-04). The GWSCREEN modeling of postulated nitrate soil concentrations at the CFA-04 indicates that this site is the most likely source of nitrate detected in the groundwater at Well CFA-MON-A-002. However, nitrogen isotope data indicated that the former sewage treatment drainfield is the source of the nitrate at Well CFA-MON-A-002.

The CFA nitrate source evaluation shows that a large number of uncertainties exist with GWSCREEN modeling. Uncertainties are associated with source concentrations, infiltration rates, stratigraphy influences such as sloping interbeds, local groundwater flow directions, and vadose zone transport parameters.

B3.3 Current Vadose Zone Monitoring Capabilities

At the CFA landfills, five neutron probe tubes are in place with three tubes located at Landfill II and two tubes located at Landfill III. One time domain reflectometry array is in place at both Landfills I and II. Five nested soil gas monitoring locations also are located near the landfills. Each nested location monitors four depths ranging from 9 to 104 ft.

B3.4 Deficiencies in Vadose Zone Understanding

Evaluation of the data from the two-year intensive monitoring program at the CFA landfills identified the following deficiencies (LMITCO 1999):

- Time-domain reflectrometry and NAT monitoring have not been conducted sufficiently over time to determine the effectiveness of the landfill cover designs. The frequency of NAT monitoring in late winter and early spring needs to be increased to ensure that any infiltration event is captured. The timing of the NAT measurements could be based on the TDR data.

- A defensible means for calibrating TDR and NAT data to soil moisture contents has not been developed.

- The ability to monitor the infiltration under the landfill covers has not been developed. The current TDR system only monitors to a depth of 2 ft. Time-domain reflectrometry probes should be installed below the E-T depth in Landfill I, II, and III. The infiltration estimates obtained from this automated TDR system need to be compared with infiltration rate estimates from the neutron probe measurements to determine the most effective means of monitoring infiltration.

- A means has not been developed to model soil gas data to determine an action level concentration that could lead to aquifer contamination approaching an MCL. The modeling would enable the establishment of action levels to evaluate whether groundwater will be impacted and whether some preventive action is required.

- A cost-effective means has not been developed to determine representative field soil moisture and unsaturated hydraulic conductivity.

- A comparison has not been made of TDR and NAT data to determine the most effective means of monitoring infiltration on a data quality and cost basis.

- Measurements have not been made with adequate frequency of soil moisture during spring thaw events.

- The precision of TDR measurements is not adequate.

- Neutron probe calibration in waste material is inadequate or uncertain.

B4. TEST REACTOR AREA

The Test Reactor Area (TRA) located in the southwestern portion of the INEEL contains high neutron flux test reactors that have been used to conduct engineering and materials tests since 1952. As originally designed and installed in 1952, two separate waste stream systems were used at the TRA, one for sanitary sewage and the second for all other waste streams. Over the years, additional segregation of waste streams has occurred. Historic disposal points include sewage lagoons, a retention basin, a warm waste pond, a chemical waste pond, a cold waste pond, Well USGS-53, and a disposal well. The primary contaminants of concern at the TRA are tritium and chromium. An aerial view of the TRA is provided in Figure B-5.

Figure B-5. Aerial view of the Test Reactor Area.

Actions that have been taken as a result of CERCLA investigations at the TRA include the termination of water disposal to the warm waste ponds, the chemical waste pond, and the sewage lagoons. A lined evaporation pond was constructed to the east of the facility to replace these disposal locations. These ponds have been capped. Water is still discharged to the cold waste ponds. An environmental assessment of the contaminated perched water system (Dames & Moore 1992) concluded that no adverse impacts would occur from contaminants in the perched water because the sources of water would be removed and the perched water zones would dry out. A monitoring program is in place to verify these conclusions (Parsons 1998).

Contaminant releases at the TRA result from disposal to seepage ponds and from an injection well. The injection well was in operation from 1964 to 1982 and was used for the disposal of cold liquid waste consisting primarily of cooling tower blowdown. Historically, water discharged to surface ponds at the TRA (approximately 0.75 million gal/day) percolated downward through the surficial alluvium and basalts. Infiltrating water from the seepage ponds formed two perched zones in the subsurface. The first was within the surficial alluvium at depths up to 50 ft. The second deep perched water zone formed when the downward movement was impeded by a low-permeability sedimentary layer at a depth of 150 ft. Water built up on top of this low-permeability layer forming a perched water table of about 400 acres in size. The residence time of water disposed of in the vadose zone has been estimated to be on the order of 7 to 8 months (Hull 1989).

B4.1 Summary of Previous and Ongoing Vadose Zone Studies

Monitoring of the perched water system at the TRA began in the early 1960s by the USGS and continues to the present. Currently, monitoring of the deep perched water zone is performed using a network of 24 wells (six used by Environmental Restoration and 18 by the USGS). Five wells in the aquifer are used for downgradient monitoring. This long monitoring history has provided a rich database from which trends in water elevations and contaminant concentrations can be easily distinguished and used as a basis for model calibration.

B4.2 Modeling

Three modeling studies have been conducted to assess the movement of water and contaminants in the vadose zone at the TRA. The first was by Robertson (1977). A series of models were built to approximate the following parameters: (1) vertical saturated flow from beneath the ponds to the deep perched zone; (2) two-dimensional radial flow within the perched water; and (3) vertical water movement from beneath the perched zone to the aquifer. The model was considered to be successful in that the results were in agreement with field observations that only solutes with low-partitioning coefficients and relatively long half-lives had entered the aquifer in detectable quantities.

A second modeling study by Dames & Moore (1992) was conducted in support of a CERCLA assessment of the contaminated deep perched water system beneath the TRA. A vertical two-dimensional slice oriented with the general groundwater flow direction was used for the simulation. Alternating fractured basalt layers and sedimentary interbeds were represented as equivalent porous media. The model was calibrated to observed perched water levels and to the observed breakthrough and historical monitoring data for tritium and chromium. This calibration was deemed successful and predictive simulations of future transport with this model were used to support a no action decision about the perched water. Several years of monitoring have been conducted since use of the chemical waste pond and warm waste pond was discontinued. Concentrations in the perched water have been decreasing slightly, but not as fast as the modeling had predicted.

The Dames & Moore modeling study acknowledged that correct knowledge of the source term and correct representation of the hydraulic gradients were more important than matching observed perched water levels in developing a model that represented observed transport. From a risk perspective this argument can be made as long as there were no unacceptable risks predicted. Had unacceptable risks been predicted, a more thorough knowledge of the controls on water movement through the vadose zone at TRA likely would have been necessary.

A third modeling study by Arnett (1996) provided flux estimates of contaminants from the vadose zone to the aquifer for the Site-Wide Environmental Impact Study. Velocities from the Dames & Moore (1992) model were used to parameterize a simplistic vertical one-dimensional model of transport through the vadose zone. This simplistic model was used with TRA waste disposal histories and a large dispersivity in the vadose zone to estimate the contaminant mass fluxes to the aquifer.

B4.3 Current Vadose Zone Monitoring Capabilities

At the present, no vadose zone monitoring capabilities are in place beyond periodic perched water level measurements.

B4.4 Deficiencies in Vadose Zone Understanding

- Several aquifer wells downgradient of TRA show high, fairly constant chromium concentrations; however, the cause is unknown because the perched water source has been eliminated. Possibilities include the following:

  - Undiscovered sources in the vadose zone or other undiscovered sources

  - Incorrect model parameters or boundary conditions; therefore, predictions do not match observations

  - A conceptual model that is unrepresentative of the TRA system

- Well PW-13, a perched water well, has measurable free product (diesel) floating in it. The source and extent are both uncertain.

B5. BOILING WATER REACTOR EXPERIMENT I AND STATIONARY LOW-POWER REACTOR NO. 1

The Boiling Water Reactor Experiment I (BORAX-I) site northwest of EBR-I is a radioactive subsurface disposal area that contains radionuclide contaminated debris and reactor components buried in place after they were damaged during a planned power excursion in July 1954 that resulted in a steam explosion. Cleanup and burial of the reactor was completed approximately 1 year after the excursion. Buried materials at the site consist of the bottom half of the reactor shield tank filled with debris, activated metal scrap, and unrecovered fuel residue. Part of the top half of the shield tank was removed and placed in the bottom half, and the remaining portion of the top half was collapsed into the bottom part using a bulldozer. The area was backfilled with clean soil, and gravel was mounded over and around the reactor for added shielding from the buried activated materials.

The Stationary Low-Power Reactor No. 1 (SL-1) Burial Ground contains radionuclide contaminated debris buried in two shallow pits and a single trench northeast of Auxiliary Reactor Area (ARA) -I and ARA-II. The debris resulted from an excursion involving the SL-1 reactor in January 1961. The excursion resulted when the reactor accidentally achieved a prompt critical nuclear reaction, which destroyed the core containment structure. The core, fuel, pressure vessel and all other parts of the reactor that were important to the post-accident investigation were removed to the Hot Shop at Test Area North (TAN) for study. A decision was made to construct a burial ground close to the site of the accident to minimize exposure to the public and site workers during cleanup operations. The SL-1 burial ground was constructed 1,600 ft northeast of the SL-1 reactor site. During cleanup, surface soils were contaminated along a corridor from the reactor site to the burial ground. Over time, wind has dispersed the contamination over an area roughly 100 ha (240 acres) in size.

Both the BORAX-I and SL-1 burial grounds were evaluated as CERCLA sites as part of the FFA/CO (DOE-ID 1991) for the INEEL. The RI/FS analysis (Holdren, Filemyr, and Vetter 1995) did not indicate groundwater pathway risks for either of these sites. Predicted surface exposure risks resulted in the emplacement of basalt rip-rap covers at each of these sites.

B5.1 BORAX and SL-1 Releases

The primary known releases at each site resulted in contamination of surface sediments in the immediate areas around each facility. These contaminated areas resulted from the excursions, cleanup activities after the excursions, and from windblown deposition. Some immediate windblown deposition has occurred from BORAX-I. For SL-1, the reactor building “contained” the contamination, and no windblown deposition of contamination occurred until the deactivation, decontamination, and dismantlement (D&D&D) activity started. The contaminants of concern were primarily fission and activation products. Releases to the subsurface from the disposed of waste have been estimated as part of the CERCLA investigations. Though no vadose zone monitoring is associated with either site, aquifer monitoring wells at each facility have shown no indication of contaminants impacting water quality from these facilities.

B5.2 BORAX and SL-1 Modeling

The groundwater pathway, including the vadose zone, for the BORAX and SL-1 facilities was evaluated using a simplistic conceptual model (Holdren, Filemyr and Vetter 1995). This model considered leaching of the contaminants, which was described using a first-order leach function, vertical one-dimensional transport through the vadose zone, and three-dimensional transport in a uniform flow field within the aquifer. The fractured basalt portions of the vadose zone were conservatively neglected.

Rather, only the estimated combined thickness of the sedimentary interbed was considered. This thickness was estimated from wells in the area and confirmed with data from new aquifer monitoring wells around ARA-I and ARA-II that were drilled as part of the CERCLA investigation. The risks evaluated with this conservatively parameterized model showed negligible groundwater pathway risks. Because the model was conservatively parameterized and because no vadose zone monitoring exists at either facility, no calibration was attempted.

A sensitivity study was conducted (Holdren et al 1999) using the same conservatively parameterized model. The sensitivity simulations investigated the effect on simulated risk of increasing the inventory by factors of 2 and 3 and increasing the infiltration rate up to 22 cm/year, the annual precipitation rate on the INEEL. Even when the upperbound inventory and infiltration estimates were used simultaneously, the predicted risks still were only marginally above 1E-06.

Based on this sensitivity analysis, the groundwater pathway was determined not to be a concern for the BORAX or SL-1 facilities. This determination allowed use of a rip-rap surface barrier over both burial grounds to reduce risks associated with surface exposure pathways. These rip-rap barriers were emplaced assuming the facilities could tolerate some additional infiltration.

B6. ORGANIC MODERATED REACTOR EXPERIMENT

The Organic Moderated Reactor Experiment (OMRE) was a 12-MW thermal reactor that operated between 1957 and 1963 approximately 6.25 km (2 mi) east of the CFA. The OMRE leach pond, located approximately 91m (300 ft) east of the OMRE facility, received reactor effluent contaminated with organic coolant and decomposition waste. Discharges to the pond could have amounted to 211,960 L (56,000 gal) of radioactive aqueous waste and 3.8 million L (1 million gal) of reactor cooling water (EG&G 1986). Three xylene releases, likely carrying radionuclides and organic compounds, to the pond were reported totaling 1,300 L (355 gal). Additional aqueous radioactive discharges in 1959, which included xylene particulate, were made to a ditch outside the OMRE (Chapin 1979). The expected contaminants include Cs-137, Co-60, Sr-90, 1,1,1-trichloroethane (1,1,1-TCA), and other organic compounds.

B6.1 OMRE-1 Vadose Zone Investigations

Passive soil-gas sampling at the OMRE was conducted to identify and delineate organic contamination within the vicinity of the old leach pond. Several contaminants were detected at the OMRE leach pond including 1,1,1-TCA, 1,2-dichloroethane (1.2,-DCA), 1,1-dichloroethene (1,1-DCE), and trichloroethene (TCE). The 1,1,1-TCA values are considered “very high” (a relative measurement level). The levels of 1,2-DCA and 1,1-DCE are substantially less than the levels of 1,1,1-TCA, and the distributions are similar. The soil-gas data suggested that subsequent sampling should be done to characterize the site. In contrast, the levels of TCE in the pond are of less concern than levels of the other contaminants discussed at OMRE. However, the distribution pattern suggests that higher levels of TCE may exist southeast of the pond in the ditch.

Currently, an investigation is under way to characterize the contamination in the OMRE leach pond. The overall objectives associated with the characterization of the OMRE leach pond follow:

- Delineate and quantify (to the nearest order of magnitude) the organic vapor plume
- Characterize the nature and extent of stained soil in the OMRE ditch and determine whether the stained soil is co-located with radionuclide-contaminated soil.

The first objective can be met with field screening data and will be addressed by an active soil-gas survey. The second objective requires field screening and definitive analytical data. Physical information such as strong odors, evidence of anthropogenic debris, and stained soil will be used during field activities to detect areas of potential contamination requiring additional characterization.

When data from the initial characterization become available, deficiencies will be determined and addressed.

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Appendix C

Conceptual Models Developed for the Vadose Zone at the Idaho National Engineering and Environmental Laboratory

Appendix C

Conceptual Models Developed for the Vadose Zone at the Idaho National Engineering and Environmental Laboratory

C1. GEOLOGIC FRAMEWORK

C1.1 Regional Geologic Setting

The Idaho National Engineering and Environmental Laboratory (INEEL) is located near the northwestern margin of the Eastern Snake River Plain (ESRP), and lies in an area influenced by two distinct geologic provinces (see Figure 1-1 of the main body of this document). The ESRP is a northeast-trending zone of late Tertiary and Quaternary volcanism that transects the northwest-trending, normal-faulted mountain ranges of the surrounding Basin and Range province. The topographically subdued ESRP, the dominant geomorphic feature of southern Idaho, is a relatively aseismic region in the midst of the high-relief, seismically active Basin and Range province.

Volcanic and sedimentary rocks of the Snake River Plain form a 60 to 100-km-wide belt, extending about 600 km from the Idaho-Oregon border to the Yellowstone Plateau. Volcanic rocks consist of late Tertiary rhyolitic rocks and latest Tertiary to Holocene basaltic lava flows. At least 1 km of basaltic lava flows and intercalated sediments has accumulated in the eastern Snake River Plain following the rhyolitic volcanism related to passage of the Yellowstone mantle plume. About 2 km of subsidence of the eastern Plain in the past 4 million years have allowed the basalts and sediments to accumulate and have confined their emplacement and deposition to the current boundaries of the Plain.

C1.2 Quaternary Basalt, Sediment, and Rhyolite

Basalts and sediments of the ESRP are part of the Snake River Group, composed largely of tholeiitic-basalt lava flows emplaced during the past 4 million years (see Figure C-1). Most eruptions were effusive, and typical landforms of Quaternary mafic volcanism on the ESRP are small shield volcanoes with summit pit craters, fissure-fed lava flows associated with zones of tensional fracturing, and relatively uncommon tephra cones of magmatic or phreatomagmatic origin (Greeley 1982).

Based on field mapping, and limited geochronometry and paleomagnetic data, Kuntz et al. (1990) (see Figure C-2) identified five Quaternary basalt lava-flow groups in the INEEL area, ranging in age from 5,200 years to greater than 730,000 years. Basaltic vents on the ESRP typically form linear arrays of fissure flows, small shields and pyroclastic cones, pit craters, and open fissures, which collectively define northwest-trending volcanic rift zones (see Figure C-3). Volcanic rift zones have similar trends as normal faults in the adjacent Basin and Range province to the north, but are not strictly co-linear with those faults. The most well-known and recently active of ESRP volcanic rift zones is the Great Rift (Kuntz et al. 1988), where eight eruptive episodes occurred at Craters of the Moon, and several smaller, monogenetic lava fields were formed during the past 15,000 years. In the INEEL area, most basaltic rift-zone volcanism seems to have occurred during Pleistocene time, generally between about 0.1 and 0.7 Ma. Most subaerially exposed lavas have normal magnetic polarity and are, therefore, younger than about 730,000 years. Several well-dated Holocene lava fields (Kuntz et al. 1986) erupted from northwest-trending fissures to the south of the INEEL, on the northeast-trending axial volcanic zone.

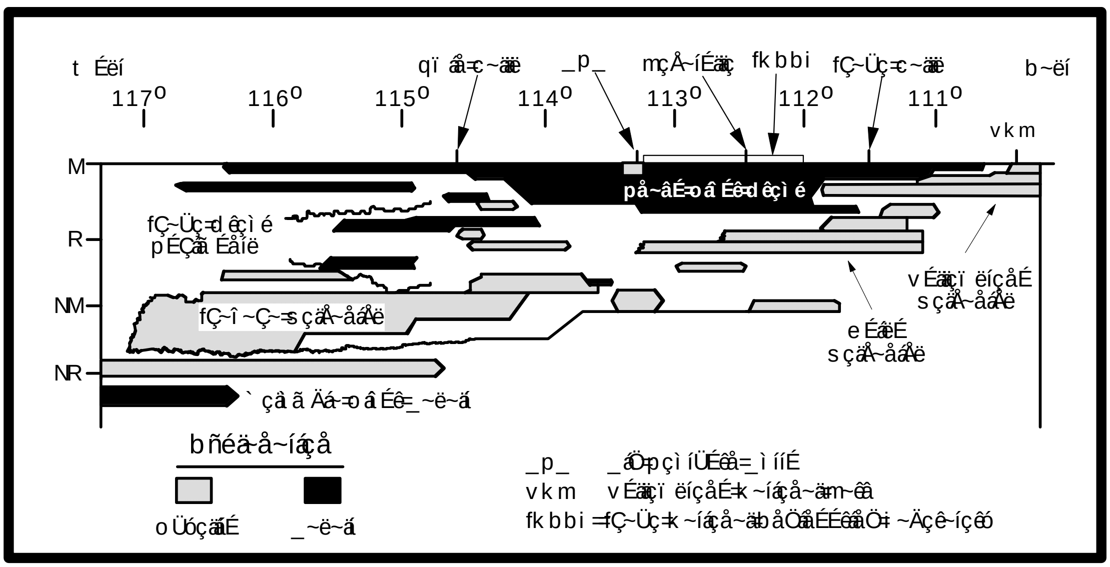
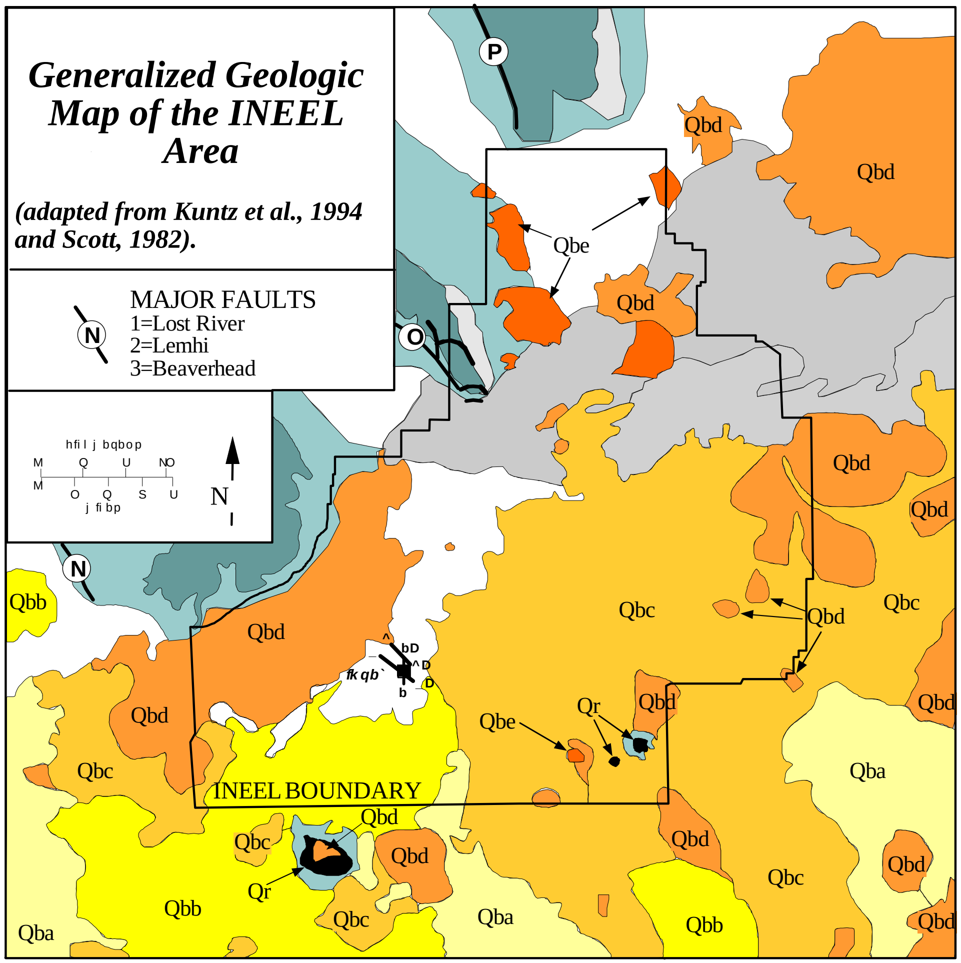


Figure C-1. Diagram of age versus longitude for Snake River Plain Volcanic Rocks (modified from Armstrong, Leeman, and Malde 1975).



Mainstream Alluvium. Includes deposits of modern flood plains (Holocene) and older deposits in terraces above modern floodplains (upper to middle Pleistocene). Composed mostly of gravel and sand with minor silt and clay. Older deposits host well developed soils and partial to complete loess cover. Up to 20 m thick in southern INEEL, and much thicker in mainstreams to the north.

Alluvial Fans Deposits. Debris flow and stream deposits of clast supported pebble and boulder gravels with matrix of silty sand to clayey silt. Holocene to upper Pliocene. Middle to lower Pleistocene units commonly locally faulted along the west flanks of the Lost River, Lemhi, and Beaverhead Ranges. Includes colluvial debris fans on steep slopes of East, Middle, and Big Southern Buttes.

Eolian Deposits. Very fine to coarse sand in mostly stabilized dunes, 1 to 5 m thick. Some areas of active deflation and migrating sand. Holocene to upper Pleistocene.

Lacustrine Deposits. Mostly lake floor deposits of Pleistocene Lake Terreton. Silty clay to sandy silt. 1 to >100 m thick. Locally includes sandy lake margin deposits and Holocene playa deposits.

BEDROCK UNITS

Basaltic Lava Flows. Black to gray pahoehoe and a'a lava flows, with bedded, oxidized, scoria, cinders, and ash near vents. Locally weathered and oxidized. Olivine basalts composed of crystals of olivine, pyroxene, plagioclase, titanomagnetite, and ilmenite in a matrix of brown glass.

Qba Holocene to uppermost Pleistocene (<15 kyr). No cover of eolian or alluvial deposits.

Qbb Upper to Middle Pleistocene (15-200 kyr). Locally covered by up to 1 m of eolian sand and loess.

Qbc Middle Pleistocene (200-400 kyr). Covered by as much as several m of eolian sand and loess.

Qbd Middle to Lower Pleistocene (400-730 kyr). Mostly covered by several m of eolian sand and loess.

Qbe Lower Pleistocene (>730 kyr) Mostly covered by several m of eolian sand and loess. Reversed magnetic polarity.

Quaternary Rhyolite (Qr)

Qr

Rhyolite Domes. Pleistocene (0.3-1.2 Myr) tan to pink, flow laminated rhyolite, with minor vent breccia and banded obsidian composed of microcrystaline intergrowths of quartz, and alkali fledspar with rare phenocrysts of quartz clinopyroxene, and magnetite.

Tertiary Volcanics

Volcanic Rocks. Basaltic lava flows, rhyolitic ash flow tuffs, and rhyolitic lava flows. Mostly Miocene and Pliocene (~4-12 Myr).

Pre-Tertiary Rocks

Pre-Tertiary Rocks. Late Precambrian to Triassic. Mostly Mississippian shelf carbonates of the Overthrust Belt. Also includes Permian to Triassic fine clastic deposits and phosphatic silts; Cambrian to Ordovician quartzites, sandstone, conglomerates, and siltstones; Devonian dolostones and argillites; and Precambrian sandstones and quartzites.

Positions at cross sections shown in figures 2.6-14, 2.6-15, and 2.6-16.

Figure C-2. Geologic map of the INEEL area showing five Quaternary lava-flow groups.

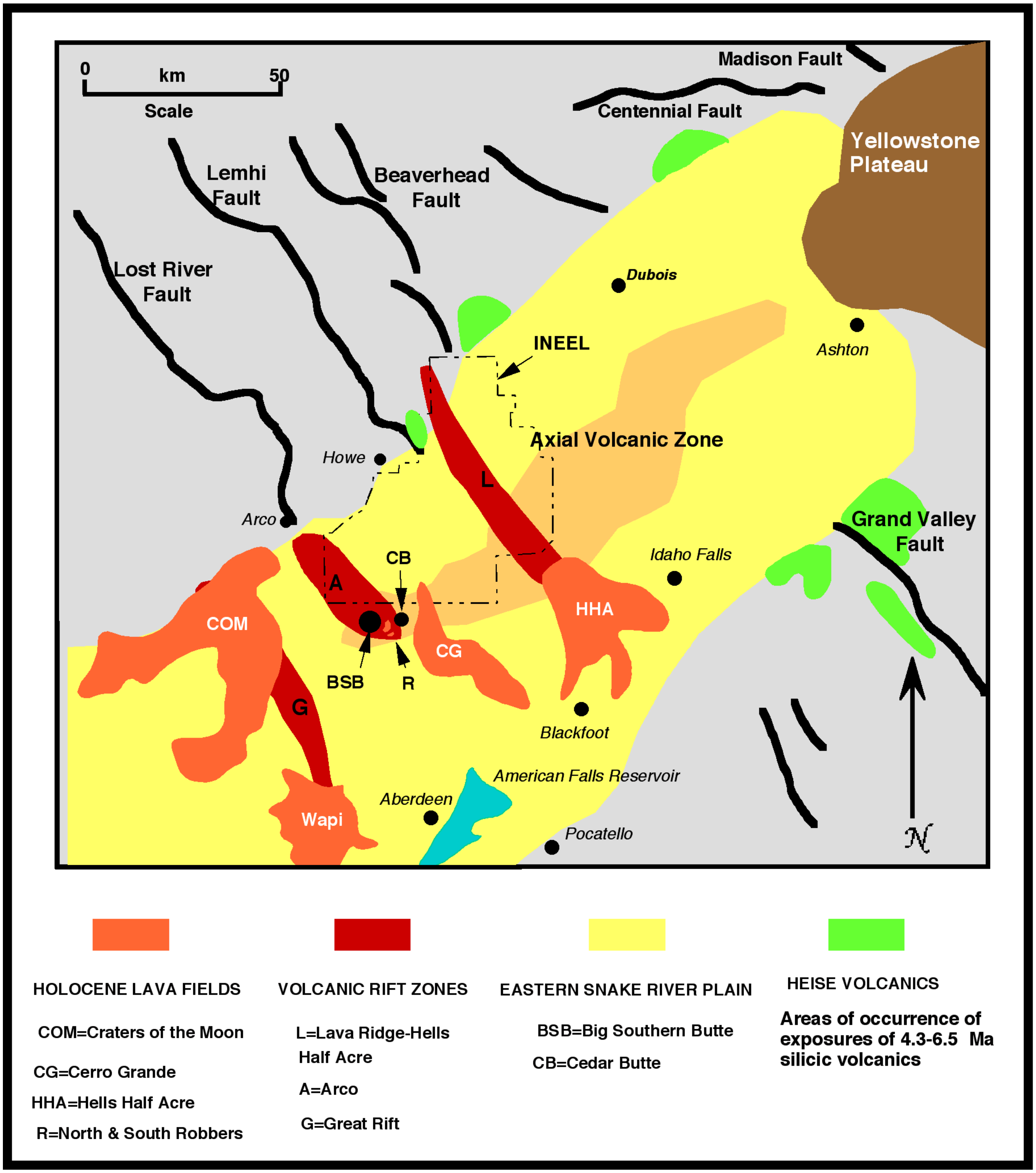


Figure C-3. Map of the Eastern Snake River Plain showing locations of volcanic rift zones, young lava flows and major faults.

C1.3 Quaternary Surficial Deposits and Sediment Interbeds

Most lava flows in the INEEL region are Pleistocene in age, have been subaerially exposed for several hundred thousand years, and are, therefore, blanketed with unconsolidated sedimentary deposits of eolian, alluvial, and lacustrine origin (Scott 1982) (see Figure C-2). Though little is known of the detailed Quaternary lithostratigraphy of the ESRP subsurface, data from INEEL drillcores (Figure C-4) generally indicate that relatively long (10^5-year) periods of sedimentation and volcanic quiescence, represented by major sedimentary interbeds, were punctuated by relatively brief (<10^2- to 10^3-year) episodes of basaltic volcanism, the latter represented by rapidly emplaced lava-flow groups (Kuntz and Dalrymple 1979; Kuntz et al. 1979, 1980; Champion, Lanphere, and Kuntz 1988; Anderson and Lewis 1989; Anderson 1991). The present distribution of surficial deposits is probably qualitatively analogous to that of subsurface deposits, involving intermittent blanketing of lava flows by loess, and the deposition of fluvial/lacustrine sediments in low-lying areas between constructional volcanic zones.

The following discussions provide information derived from examination of surficial deposits in the INEEL area, but they can be viewed as models for depositional processes responsible for sediment interbeds between lava flows at depth.

C1.3.1 Alluvial Deposits

Alluvial deposits of two types are found in the INEEL area: alluvial-fan deposits and mainstream alluvium. Alluvial fans are developed on the steep lower flanks of basin-and-range mountains and contain clastic material of local origin, commonly subangular or subrounded, moderately sorted gravel, dominated by Paleozoic carbonate clasts.

Mainstream-alluvial deposits are associated with the channels of the Big Lost River, Little Lost River, and Birch Creek, which longitudinally drain the northern Basin and Range province and flow southward onto the ESRP (Pierce and Scott 1982). None of these streams reaches the Snake River to the south. Instead, their ephemeral waters percolate into permeable lava flows and sediments at the Lost River Sinks of the northern INEEL, a local recharge area for the Snake River Plain aquifer. Mainstream deposits are generally better sorted, rounded, and bedded than those of alluvial fans, and clasts are predominantly quartzite, chert, silicified Eocene volcanic rocks, and other resistant lithologies.

C1.3.2 Lacustrine Deposits

Volcanic eruptions and tectonism have periodically impounded the Snake River and its tributaries, forming lacustrine basins or areas of impeded drainage (Malde 1982; Howard, Shervais, and McKee 1982; Scott et al. 1982; Hackett and Morgan 1988). In the INEEL region, the axial volcanic zone obstructed drainage from areas north of the ESRP. During glacial/pluvial periods, the resulting basins received more runoff than now, and contained large shallow lakes, in contrast to the present small playas of the Lost River Sinks. One such basin in the area that is now the northern INEEL was occupied by Lake Terreton, from which Pleistocene deposits have been cored in the upper part of Drillhole 2-2A (see Figure C-2). Lake Terreton formerly covered a wide area near the present Mud Lake. Its shoreline generally follows the 4,800-ft topographic contour on the ESRP and is marked by beaches, bars and deltas. Lake Terreton sediments are the major source of material for Holocene dunes to the northeast.

C1.3.3 Eolian Deposits

Pleistocene loess deposits are widespread on the ESRP, and reach their greatest thickness along its southeastern margin. Several episodes of loess deposition are inferred from studies of loess stratigraphy and paleopedology (Pierce et al. 1982; Lewis and Fosberg 1982; Scott 1982). Holocene basalt

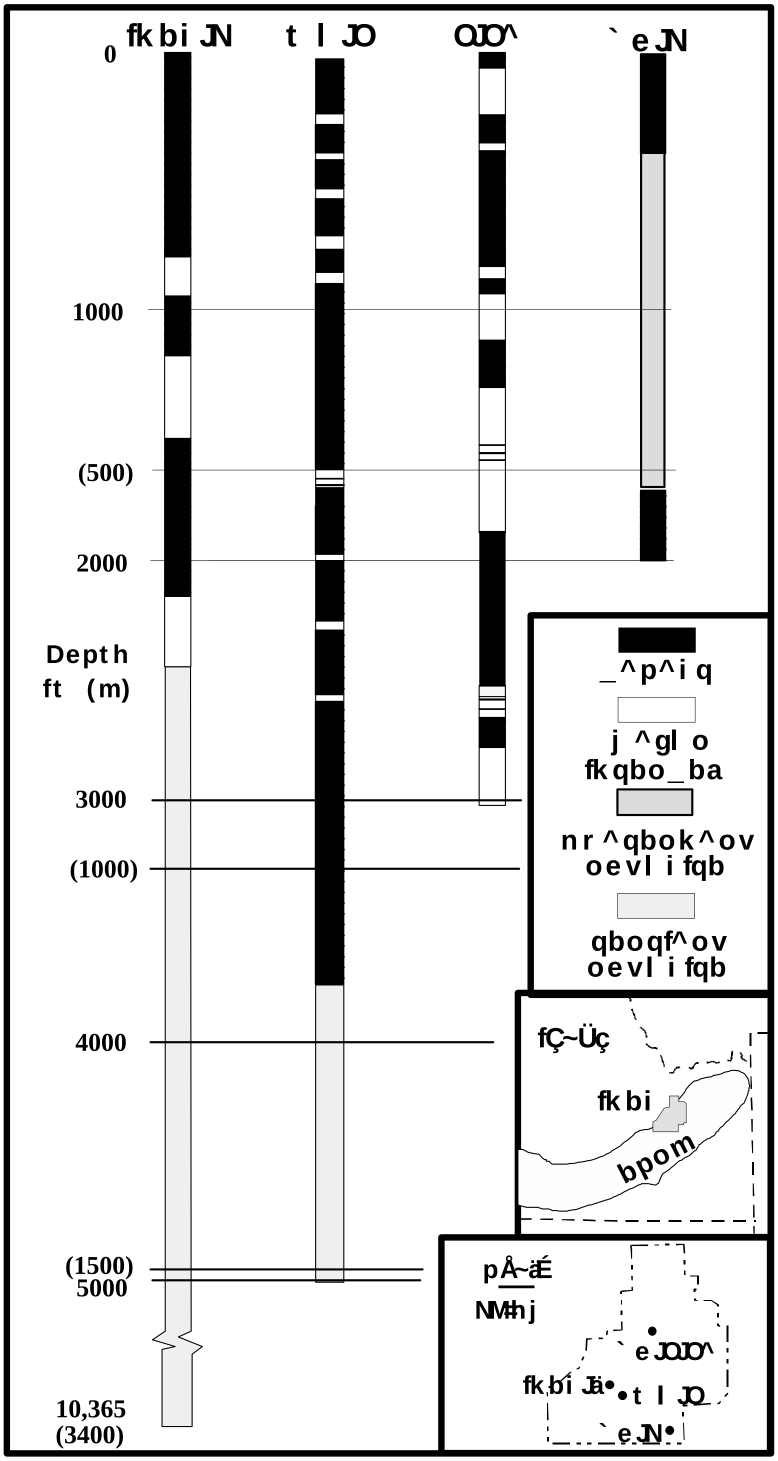


Figure C-4. Simplified lithologic logs of four deep INEEL drill holes.

flows on the ESRP have accumulated little or no loess (Kuntz et al. 1986), indicating that major loess deposition ceased about 10 to 15 ka. Late Pleistocene basalt flows and geomorphic surfaces are overlain by a single loess blanket, whereas older surfaces are generally mantled by several loess units, separated by paleosols or erosional surfaces. Pierce et al. (1982) identified two widespread loess units in southeast Idaho: the upper loess (Unit A) was deposited about 10 to 70 ka, while the lower (Unit B) is dated less specifically but probably accumulated about 140 to 200 ka. Dunes and sheets of Holocene eolian sand near Mud Lake (see Figure C-2) are deflated from the alluvial surfaces of the Lost River Sinks, and from the abandoned shoreline, and floor of former Lake Terreton to the southwest.

C1.4 Sediment Interbed Distribution and Thickness

The distribution and lithology of sedimentary interbeds within the basalt section beneath the INEEL area exerts a strong influence on the flow of groundwater in both the vadose and saturated zones. It has been postulated that a thick sequence of fine-grained, relatively impermeable, lake sediments in the Mud Lake area impede groundwater flow and cause the steep gradient in the water table there (Lindholm et al. 1983; Lindholm and Goodell 1986; Garabedian 1989). In contrast, interbed distribution and lithology may enhance aquifer flow in the central part of INEEL. The distributions of interbeds in a cross section that traverses the Big Lost River and extends from the Plain margin to East Butte (see Figure C-5) shows that there are numerous interbeds beneath the present course of the river, and that they become less numerous and thinner with distance from the river. There is likely to be a mixture of both coarse-grained (sands and sandy gravels representing channel and terrace deposits) and fine-grained (silts and silty clays laid down as overbank deposits) interbeds deposited by the Big Lost River as it was pushed back and forth by lava-flow emplacement during the past several million years. Eolian deposits of both loess and sand also are likely to be present. Based on drillhole information from throughout the INEEL, two interpretations of interbed distribution are shown in Figure C-5, one assuming a very short horizontal continuity of interbeds (more of a river channel interpretation), and one assuming a long horizontal continuity of interbeds (perhaps representing broad flood-plain development such as the river exhibits today). In either case, however, there is a concentration of northward-elongated (perpendicular to the plane of the cross section) alluvial interbeds in the central portion of INEEL. The presence of these interbeds beneath most of the major facilities at INEEL provides important controls on transport of water and contaminants in the vadose zone.

The thickness of sediment interbeds is extremely variable at both local (even within individual interbeds) and regional scales (see Figure C-6 and Table C-1). Thickness statistics were developed from the electronic database of well lithologies developed by Anderson et al. (1996). Additional analysis shows that there is a tendency for interbed thickness to be greater in the northern than in the southern portions of the INEEL because of the presence of thick lake sediments there. There may be significant aliasing of the data because no attempt was made to account for different depths of wells. Some of the thickest beds occur only deep in the deepest boreholes, and because there are only a few deep boreholes, the data set is likely skewed toward thinner interbeds.

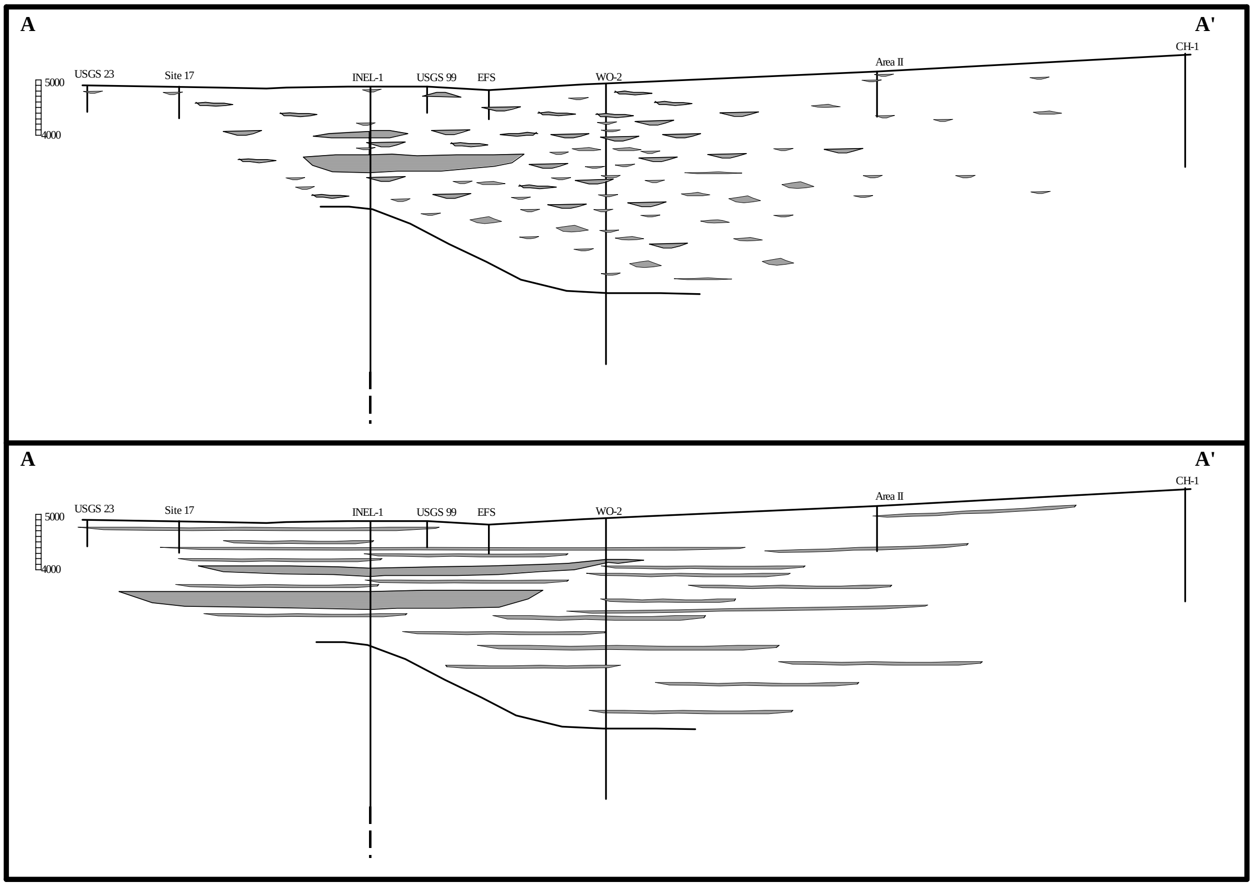


Figure C-5. Sediment interbed distribution across the INEEL.

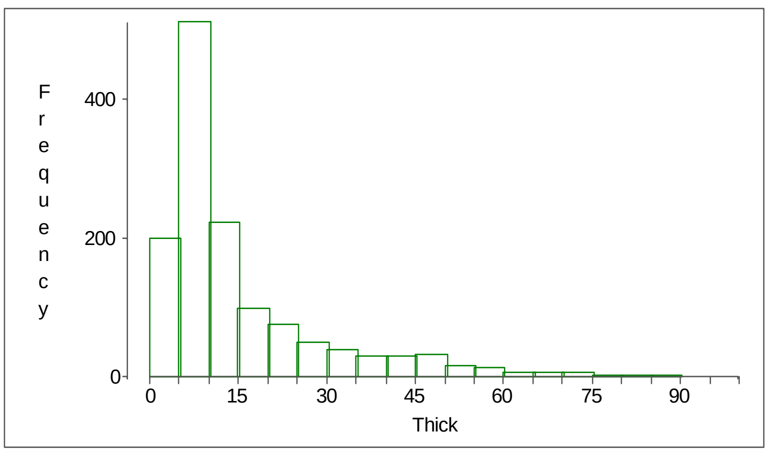


Figure C-6. Histogram for sediment interbeds from all INEEL wells.

Table C-1. Thickness statistics for sediment interbeds from all INEEL wells.

Minimum	1
Maximum	533
Median	9.0
Mean	10.9
Standard deviation	0.403277

C1.5 Characteristics of Basalt Lava Flows

C1.5.1 Lava Flow Facies

During emplacement of ESRP basalt lava flows, molten rock is continuously supplied to the advancing flow front through lava tubes. The solidified crust on the top, bottom, and ends of the lava flows is kept inflated by the pressure of the molten material in the interior of the flow. As the flow front advances, the crust at the end of the flow is laid down and overridden by the new lava, and the upper crust is stretched, broken, and fissured by movements of magma beneath. This “bulldozer tread” type of emplacement mechanism produces distinctive facies within each lava flow. An idealized section showing distribution of vertical and horizontal facies variation in ESRP basalt lava flows is shown in Figure C-7. From bottom to top, basalt lava flows typically are composed of a basal rubble zone, a lower vesicular zone, a massive columnar jointed zone, an upper vesicular and fissured zone, and a cap of platy-jointed crust.

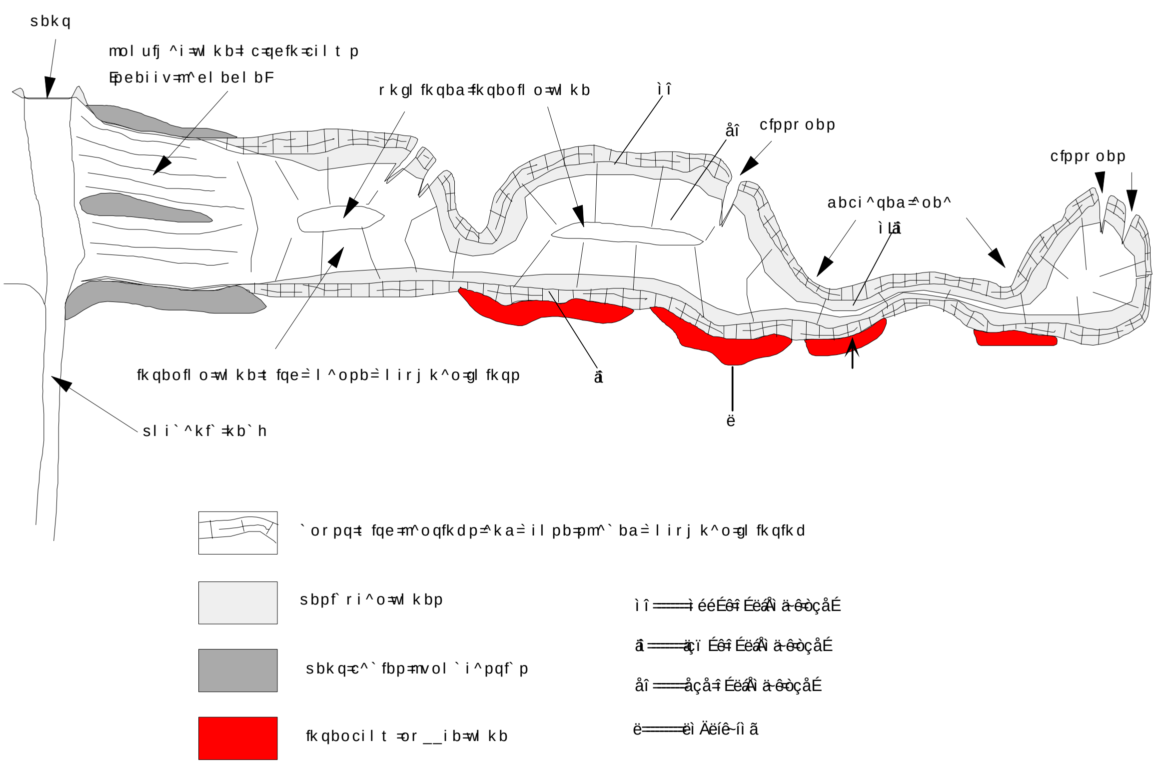


Figure C-7. Longitudinal cross section of a typical basalt lava flow on the Eastern Snake River Plain.

The near vent facies of lava flows is typified by thin, vesicular, platy flows (shelly pahoehoe). Also pyroclastic ash and breccia layers are commonly interleaved within the thin flow layers. With distance from the vent, the shelly pahoehoe grades rapidly into the layered facies structure, described above, which typifies the medial and distal portions of the lava flow (see Figure C-7). Deflation pits, in which solidified crust has subsided over areas where lava has drained away, are common throughout the flow but more numerous near the terminus.

C1.5.2 Lava Flow Dimensions

There is a great range in length, area, and thickness of lava flows in the INEEL area (see Table C-2). The length and area measurements are for lava flows exposed at the surface, and are measured from geologic maps (Hackett, Smith, and Khericha 2000). The thickness measurements are mostly from drill hole information in the Radioactive Waste Management Complex area, augmented by measurements made of lava flow thickness in cliff faces in the Box Canyon area, to the west of INEEL (Knutson et al. 1989, 1992).

Table C-2. Statistics of lava flow dimensions.

	Length	Area	Thickness
	(km)	(km^2)	(m)
Minimum	0.1	0.5	1
Maximum	31	400	34
Range	30.9	399.5	33
Mean	12.4	96.5	?
Median	10	70	7
Standard deviation	7.9	94.2	?
Number of measurements	46	43	641

C2. VADOSE ZONE HYDROLOGIC CONCEPTUAL MODEL

This section presents the current level of understanding of water movement in the subsurface at the INEEL. The section is organized in terms of the general movement of water in the subsurface, following the path of water from land surface to the Snake River Plain Aquifer. Figure C-8 graphically shows the vadose zone at the INEEL, the sources of water, and the movement of water in different parts of the vadose zone. This conceptual model is derived from both field observations from a variety of investigations conducted at the INEEL since the 1960s and from hypotheses. By including hypotheses, the conceptual model will not necessarily agree with the conceptual models of each and every researcher working on vadose zone issues at the INEEL. However, it will contain enough common elements to be satisfactory to most researchers.

In general, the movement of water in the INEEL subsurface is extremely complex to describe because of spatial variability of hydraulic properties, temporal changes in the hydrologic regime caused by seasonal changes, limited access locations with vertical wells in areas where horizontal permeability is a dominant control, heterogeneous waste disposal, lack of integrated sampling opportunities in the vadose zone like pumping tests in t he aquifer, and limited duration of monitoring activities. With these limitations in mind, the remainder of this section describes a vision of water movement in the subsurface.

C2.1 Sources of Water at Surface

Several sources of water contribute to water movement in the vadose zone. Direct precipitation contributes some water to the subsurface. The annual precipitation at the INEEL is approximately 22 to 23 cm/year. A variable portion of this annual precipitation is received as snow, which accumulates until a melting event occurs. Runoff of precipitation can occur during substantial rain events or from snowmelt events. Flooding from runoff in local basins on the INEEL can supply substantial amounts of water when those events occur.

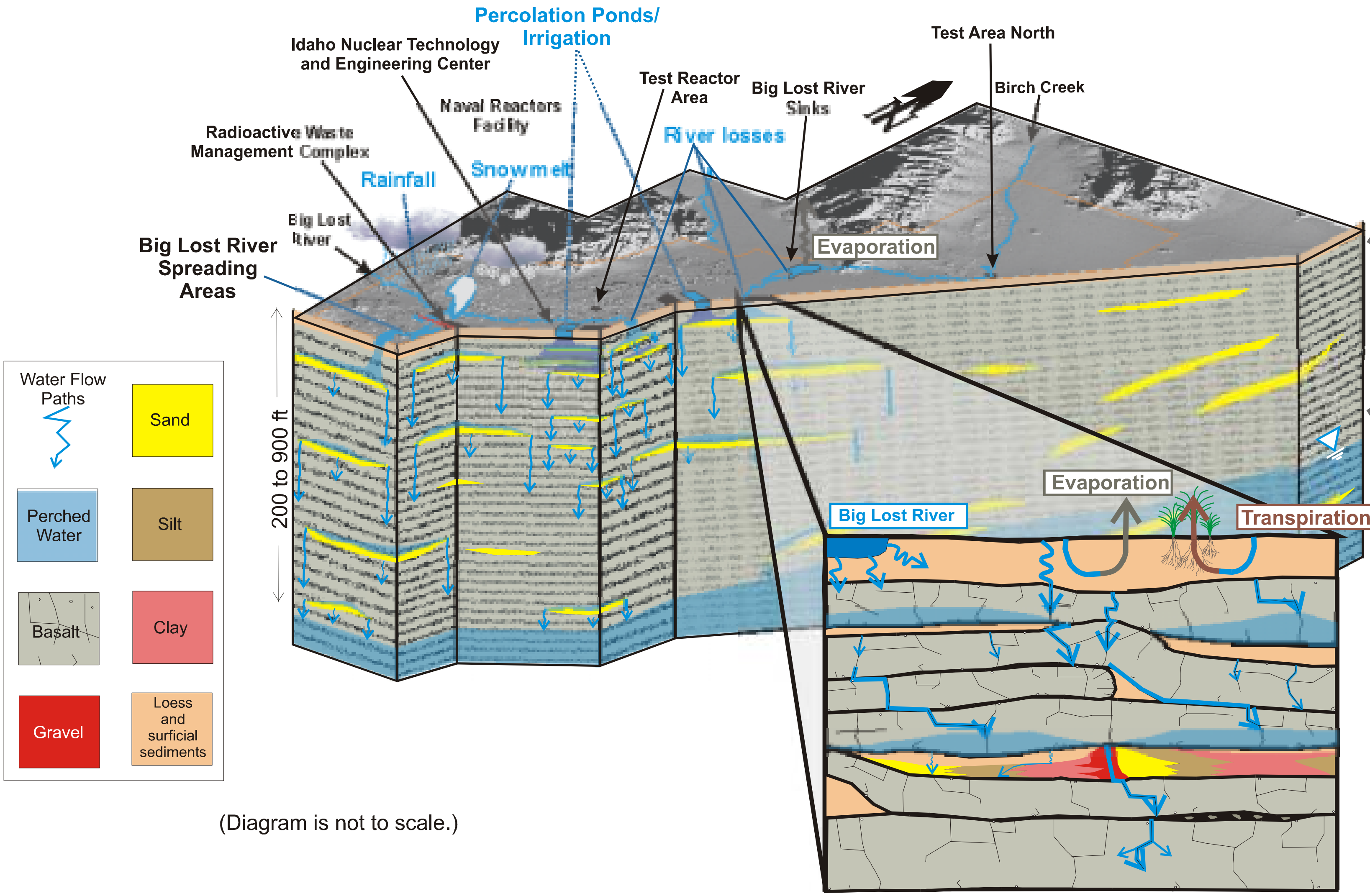
In addition to precipitation, another source of water is surface water that flows onto the INEEL from several drainages to the northwest. These drainages are the Big Lost River, the Little Lost River, and Birch Creek. Depending on the snow pack and precipitation that occur in a particular year, these water sources may flow all year, or they may be completely used up for irrigation prior to reaching the INEEL. The amount of water reaching the vadose zone from these surface water sources depends on the proximity to the surface sources.

A third source of water that contributes to water movement in the vadose zone is anthropogenic activities at the INEEL facilities. These sources include sewage treatment ponds, infiltration galleries, and disposal of process water at some facilities. Where these anthropogenic sources exist, they usually supply a far greater amount of water to the subsurface than precipitation.

C2.2 Surface Infiltration

Infiltration of water from the surface into the subsurface is known to be spatially and temporally variable. At the INEEL, infiltration primarily occurs in early spring, when the accumulated snow pack melts and there is essentially no evapotranspiration. Exceptions to this, however, include infiltration resulting from summer thundershowers.

The primary controls on where, when, and how much water infiltrates at any one place are the following:



(Diagram is not to scale.)

Figure C-8. Geohydrologic conceptual model of the vadose zone at the INEEL.

- The degree of soil freezing (results from cold weather conditions and a lack of snow pack)
- Disturbances of natural layering in soils that disrupts low permeability layers, or disrupts high permeability layers that act as capillary barriers
- Depressions in surface topography that collect meltwater
- The magnitude of potential evapotranspiration that is occurring and the depth to which evapotranspiration affects water movement
- Spatial variability in hydraulic properties
- Presence of preferential pathways that allow rapid infiltration.

The controls on infiltration listed above are primarily for infiltration that is occurring as a result of widespread precipitation or snowmelt. In addition to this infiltration mechanism, infiltration occurs from the surface sources and anthropogenic sources under saturated conditions. The controls on this type of infiltration include the following:

- Hydrologic properties of the sediments under the river, spreading areas, or infiltration ponds
- Height of water or head
- Duration of water being present.

Once the water infiltrates into the surficial sediments past a depth where it can be affected by evapotranspiration, it primarily continues to move downward under the influence of gravity, though capillarity can exert an influence that can move water laterally from wetter to drier locations.

C2.3 Water Movement from Surface Sediments into Basalt

As water moves downward through the surficial sediments, it eventually encounters an underlying fractured basalt flow. Multiple mechanisms are possible by which water can continue moving downward into this lithologic unit. These are illustrated graphically in Figure C-9. All these mechanisms likely occur to varying degrees. The difficulty is in assessing their relative contribution to net water movement under a range of hydrological conditions from dry to wet.

The first mechanism illustrated in the figure is movement from the pore space of the sediments into the pore space of the matrix. This process likely takes place predominantly in locations where there is not sufficient water to elevate moisture conditions at the interface.

The second mechanism is closely related to the first and consists of water movement from the pore space in the sediments into a very small aperture fracture that exerts a capillary imbibition force on the sediment pore water. This process, similar to the first, also likely takes place in predominantly drier locations.

The third mechanism describing water movement at this interface consists of lateral movement of water along the interface. This movement would occur when the moisture flux moving vertically through the surficial sediments is greater than the hydraulic conductivity of the underlying basalt matrix, and when there are no open fractures in the basalt. This lateral movement could occur with or without the

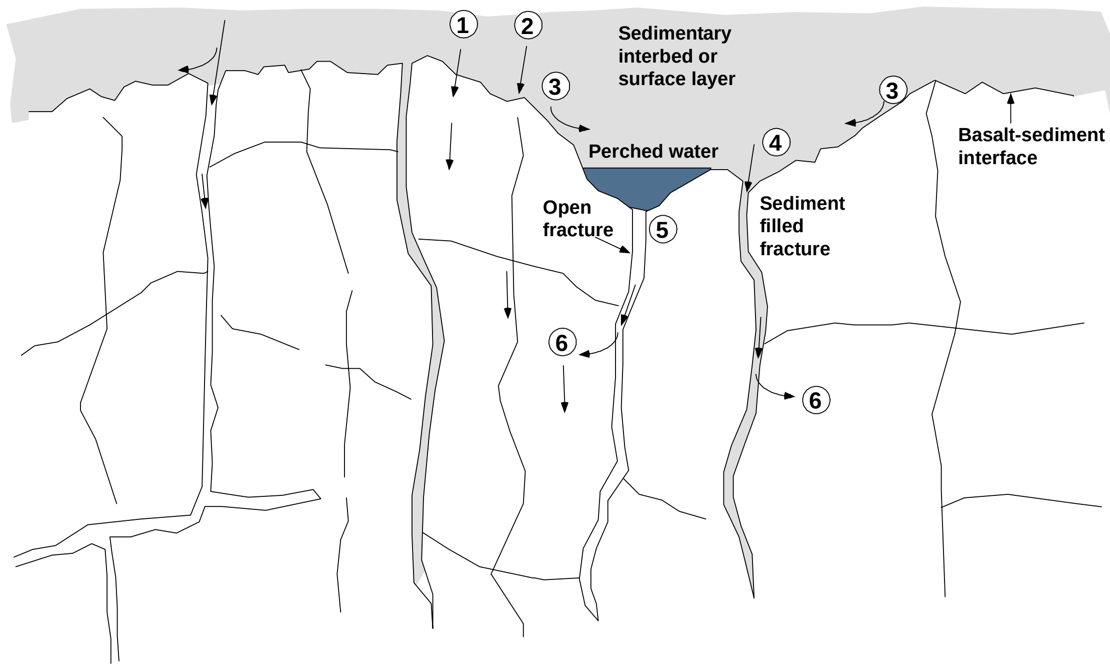


Figure C-9. Possible mechanisms by which water can move across a sediment/basalt interface.

presence of perched water. If perched water conditions form, the magnitude of the lateral flux could be greater. This horizontal movement of perched water is believed to have been observed in neutron access tube moisture monitoring in the CFA landfills (Keck et al 1995). Because the vertical permeabilities of the basalt matrix are generally less than the overlying sediments, it is likely that some horizontal movement occurs frequently.

A fourth possible mechanism of water movement across this interface is when water moving laterally or vertically encounters a sediment-filled fracture into the underlying basalt. The sediment in the fracture is derived from the sediment overlying the fracture and will have a similar hydraulic conductivity allowing water to move vertically downward through it.

The fifth, and potentially dominant, mechanism by which water crosses the sediment-basalt interface occurs when perched water accumulates at the interface and encounters an open fracture. Depending on its aperture, the fracture will likely not allow water to enter until perched conditions occur. Once perched conditions occur, an air-entry potential is reached and a pulse of water will enter the fracture. Depending on the conditions, this pulse may have a greater magnitude of water than all the previous mechanisms combined.

This presentation of water movement from the surficial sediments into the basalt conveniently ignores some complications, such as the presence of a low-permeability clay layer at some locations, such as is often found at the base of the surficial sediments inside the Subsurface Disposal Area. In these cases, the dominant mechanisms may be different, or they may be the same but even more dominant because water may perch and move laterally even farther until it encounters a fracture or preferential pathway into the fractured basalt.

C2.4 Water Movement Within Basalt Flows

The movement of water within the fractured basalt is the least-understood portion of the subsurface pathway. Any conceptual model for this portion of the subsurface is primarily based on hypothesis. Part of the reason for this is the limited number of observations that are available from which to draw conclusions. Several hypotheses are viable for describing water movement in this fractured basalt region including both Darcian and non-Darcian flow. These conceptual models are likely applicable under different conditions.

Under saturated conditions (e.g., flooding or high surface infiltration), the primary water movement in this region will be within the system of fractures. The fracture will control the movement of water because of their high permeability compared to the basalt matrix. This type of water movement will result in a rapid advance of a wetting front through the entire fractured basalt portion of the subsurface. Monitoring of the advance of the wetting front in the Large Scale Infiltration Test (Wood and Norrell 1996) confirmed this rapid movement. If this movement is the dominant mechanism that is being considered, it may be appropriate to represent this portion of the subsurface as an equivalent high-permeability, low-porosity media. The degree to which this approach is representative is subject to qualitative discussions. For risk assessment purposes, the approach may be adequate. For actually understanding and representing the physical mechanism, this approach almost certainly is invalid.

Under less than saturated conditions, the mechanism of water movement in the fractured basalt is less certain. One hypothesis is that the open fractures will act as capillary barriers and water existing as films on the fracture walls will be imbibed into the fracture matrix. (mechanism 6 in Figure C-9) (Wang and Narasimhan (1985). In this case, water movement would be primarily within the low-permeability basalt matrix and would behave as Darcian flow. Other hypotheses that have non-Darcian flow regimes as their basis include film flow along the walls of the fractures and chaotic falling drips.

No matter what the mechanism of water movement in the fractures, there will still be some interaction with basalt matrix. The basalt matrix has been observed to have matric potentials in tensiometric range at the INEEL, indicating relatively wet conditions. This increases the likelihood of interaction between water in the basalt matrix with water moving in fractures. In the cases where water and contaminants interact between the fractures and the basalt matrix, a dual continuum representation is required for numerical simulation.

Under extremely dry conditions, it seems reasonable that the majority of water movement will be within the basalt matrix by Darcian flow. Under these conditions, some movement of water could still occur along fracture walls, however, as a result of heterogeneity and preferential pathways in the fractured basalt.

In any case, the fractured basalt is extremely heterogeneous with preferential pathways caused by the presence of fractures. When water movement occurs in the preferential pathways, only a limited portion of subsurface is involved in transmitting water. Some portions of basalt flows are more fractured than others, according to the geologic model (Knutson et al. 1992).

The extent to which water moves horizontally while vertically transiting the fractured basalts is uncertain. Under conditions of a wetting front resulting from ponding in the Large Scale Infiltration Test, evidence of lateral water movement in the region under the basin was observed. However, on a larger scale there was no evidence of lateral migration even 50 ft outside the basin as water moved primarily vertically downwards. This was the case until the infiltrating water encountered a sedimentary interbed, perched, and then spread laterally.

If no sedimentary interbeds are present at a location where infiltration occurs, rapid water movement down to the aquifer will occur. This rapid movement down through the vadose zone has been observed in USGS monitoring wells on the INEEL (USGS 1963). At one location on south central portion of the INEEL, Well 5 showed a definite rise in water level about 15 to 20 days after the beginning of the spring thaw that was attributed to infiltration of snowmelt in local basins at land surface.

C2.5 Water Interaction with Sedimentary Interbeds

Where sedimentary interbeds are present in the subsurface, they have a large effect on downward movement of water. This occurs because of a permeability contrast between the interbed, the fractures, and basalt matrix. One primary result of this contrast is the development of perched water in association with the interbeds.

The exact mechanism causing perching is unknown but is hypothesized to include the following:

- Low permeability lenses within interbeds
- Low permeability of interbeds compared to fractured basalt
- Infilling of fractures both above and below the interbeds with clay particles.

Most fractures in the subsurface have a clay lining (Rightmire and Lewis 1987). These clay particles can be hypothesized to migrate with pulses of infiltrating water. It is easy to conceptualize these particles migrating downward to the interbed through the open fractures where they then get filtered out when the water encounters the interbed. As these particle accumulate above the interbed, they fill up the fracture. Because these particles are primarily fine-grained clay, they have a low permeability. If the basalt matrix over the interbed has a low enough permeability, the combination of the basalt matrix and the clay-filled fracture also will have a low permeability and will lead to development of perched conditions. An example of this situation has likely been observed at the SDA. As a vadose zone monitoring well (Well USGS-92) was being drilled at the SDA, perched water was observed while the well was being drilled in basalt above an interbed at a depth of approximately 200 ft. As the drilling just proceeded into the interbed at this location, the perched water drained into the interbed. Drilling stopped and the interbed portion of the wellbore was sealed. Perched water recovered and has been present since 1972.

Infilling of fractures below the interbeds could result by several methods. Mobilization of fine clay-particles could occur as a result of transient pulses of water impact the interbeds. More likely is that the infilling occurred when the basalt flows were first exposed at land surface as surficial sediments were laid down to become future interbeds.

Because the interbeds are composed of porous sediments, Darcian flow is believed to describe water movement across the interbeds. Though they are limited in vertical extent, the interbeds do have some capacity to store transient pulses of water from above and release them more slowly to the underlying fractured basalt. This storage capacity results in a damping of transient infiltration pulses as water from an infiltration event moves vertically across a sequence of interbeds. This conceptual damping has been captured in numerical simulations of subsurface flow and transport performed for the SDA and INTEC facilities.

Water that transits the interbeds will enter the underlying basalts via the same mechanisms that were discussed above for the migration of water from the surficial sediments down into the fractured basalt.

C2.6 Infiltrating Water Reaches Snake River Plain Aquifer

Eventually, water infiltrating at the surface of the INEEL will reach the underlying Snake River Plain Aquifer. Though the aquifer is not technically part of the vadose zone and, therefore, not in the scope of this document, nonetheless some important interactions occur as the water that infiltrated at the surface encounters the aquifer.

In the majority of locations, this encounter between infiltrated water and the aquifer is expected to occur within fractured basalt because fractured basalt comprises the majority of the vadose zone. The presence of fractures makes a large capillary fringe zone unlikely. The degree of interaction between the infiltrating water and water flowing horizontally within the aquifer depends on water velocity within the aquifer. This horizontal velocity is spatially variable because of spatial variability of hydrologic properties and preferential pathways within the aquifer.

Changes in water levels in the aquifer have been observed over periods of weeks to months. As the water level rises or falls, the movement of water (and contaminants) from the vadose zone into the aquifer will be affected. Within the aquifer, horizontal permeability generally becomes more important than the vertical permeability.

C2.7 Summary

This section provides a discussion of the various mechanisms that are thought to control water movement in the various portions of the subsurface. The level of confidence varies between the sediment portions of the subsurface where the flow mechanisms are reasonably well understood and the fractured basalt portions where the mechanisms are less well known.

C3. PHYSICAL PROCESSES OF CONTAMINANT TRANSPORT IN THE VADOSE ZONE

Contaminant mass transport in the vadose zone is affected by a number of processes including the physical phase that the contaminant occupies and the transport mechanisms within each phase. These processes are mathematically described in numerical transport models in an attempt to predict contaminant distribution, concentration, or flux, both spatially and temporally. Concurrent with the physical transport, chemical processes transform the contaminant during its transport, further complicating the prediction. It is important to conceptually understand the possible transport mechanisms and chemical transformation of the contaminant along with the correct mathematical description in the numerical model to correctly predict the contaminant distribution. Furthermore, an understanding of the processes and the scale in which they are applicable is required to make the necessary parameter measurements needed for the numerical predictive model. This section briefly describes the physical processes of contaminant transport. Chemical processes are described in the following section.

The type of contaminant, method of release, and vadose zone properties all determine the physical phases that the contaminant occupies for mass transfer. Potential physical mechanisms for contaminant transport include (1) mass flux of the dissolved chemical movement within the soil-water, (2) gaseous mass flux through the void space, (3) pure liquid mass flux through the soil pores, and (4) the sorbing of contaminants onto colloidal particles and subsequently transport with the soil-water. An illustration of the source term and contaminant migration conceptual model for the INEEL vadose zone is provided in Figure C-10.

Advection and dispersion in the water phase transport contaminants dissolved in the pore water. The rate of advective transport is equal to the average linear velocity of the water. Dispersion describes the spreading phenomenon of a contaminant in a porous medium. It is a nonsteady irreversible process in the sense that if the flow were reversed, the initial distribution of the contaminant could not be recreated. The current state of scientific knowledge assumes that dispersion comprises two processes: mechanical dispersion and molecular diffusion. The mechanical dispersion is created by velocity variations at the microscopic level. Molecular diffusion is caused by the random movement of contaminant molecules in a fluid creating a flux from higher to lower concentrations.

Organic liquids and some inorganic materials have the potential for transport in the gas phase. In addition, some radionuclides (mainly ^{14}C as CO_2 or as CH_4, and ^{3}H as water vapor) also can be transported in the gas phase. Contamination within the gas phase usually results from the partitioning of the contaminant from a liquid or dissolved phase by vaporization or biological processes and is highly dependent on the temperature. Mass transport within the gas phase occurs by diffusion and by convection (if the gas phase is moving). A common assumption is that no gas advection occurs. However, researchers have suggested that this may not be the case in fractured systems because of barometric pressure fluctuation.

Nonaqueous-phase liquids (NAPLs) can be transported through the vadose zone as a pure phase. A NAPL is an organic liquid that is immiscible with water and, therefore, exists as a liquid phase that is separate from water. Nonaqueous phase liquids can be classified based on their density relative to that of water. A light nonaqueous phase liquid (LNAPL) is less dense than water, and a dense nonaqueous phase liquid (DNAPL) is more dense than water. Because of these density contrasts, the behavior of LNAPLs and DNAPLs in the subsurface is quite different. Light nonaqueous phase liquids float at the water table and thus their depth of penetration is limited, while DNAPLs sink below the water table and thus can penetrate to great depths in groundwater systems.

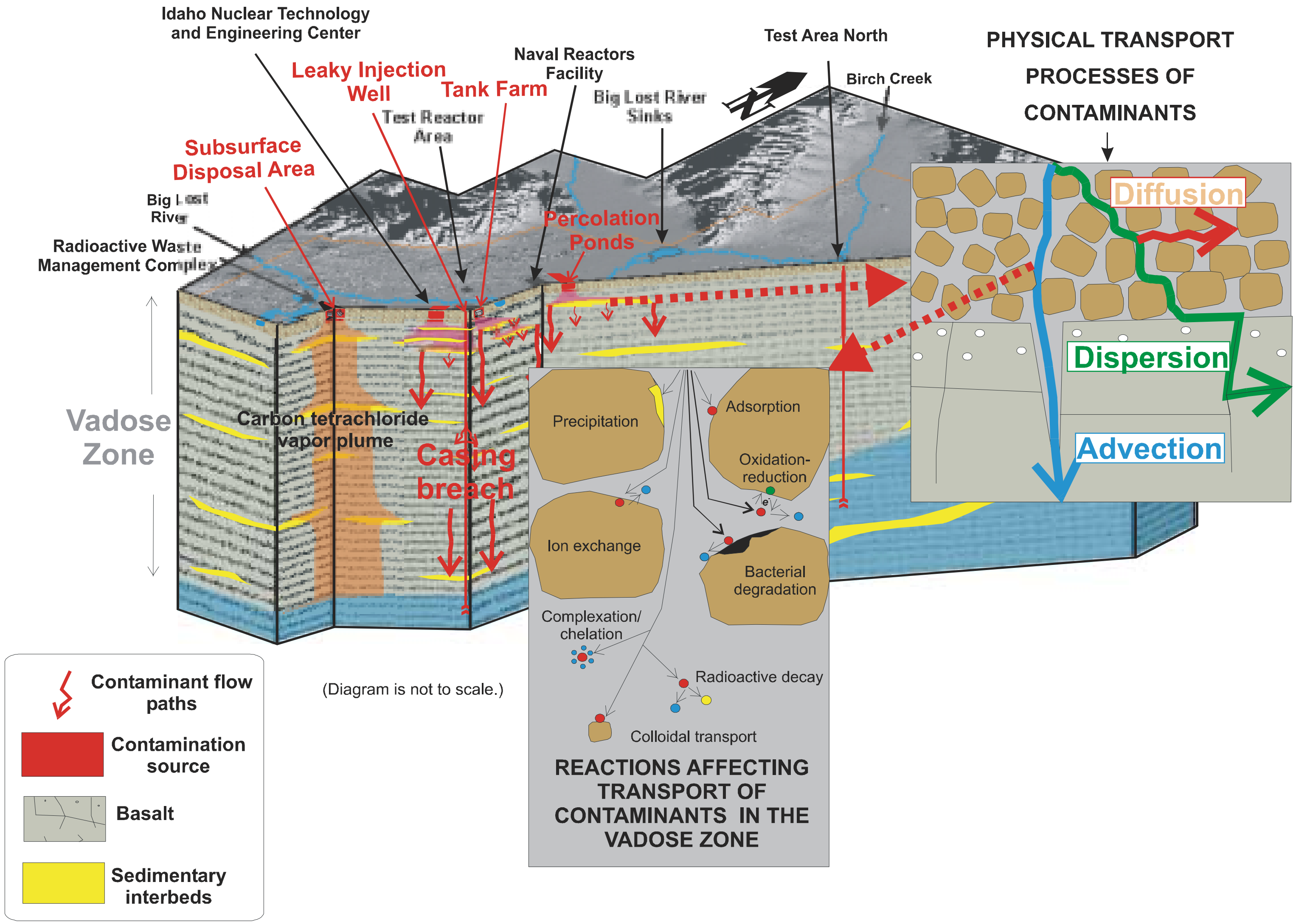


Figure C-10. Source term and contaminant migration conceptual model of the vadose zone at the INEEL.

Pressure and gravitational gradients drive NAPL transport in the vadose zone. The movement of a NAPL away from the initial source area can subsequently serve as an additional source for dissolved or gas phase transport. The extent of NAPL transport is dependent on the volume of the NAPL release, the area of infiltration, the time duration of the release, properties of the NAPL and the media, and subsurface flow conditions (Mercer and Waddell 1993). Residual NAPLs can be a source of subsequent gas and dissolved phase transport.

Colloidal transport of contaminants can be viewed as special case of contaminant transport. Colloidal transport of contaminants occurs when contaminants sorb onto small particles (10^{-6} to 10^{-9} m) and are subsequently transported with the advective flux of the water. Plutonium and ^{60}Co and possible ^{137}Cs migration have been attributed to colloidal-assisted transport at Hanford (Boutin 1999). Chemically and physically, colloids behave differently from dissolved species. Some researchers have concluded that contaminated colloids can be transported faster than if the contaminant were in its dissolved form. Conversely, colloids may be retarded by filtration in the soil. Colloidal transport becomes more likely in saturated or unsaturated fracture flow (Parsons, Olague, and Gallegos 1991).

Multi-phase transport must be considered in evaluating the overall mass transport of a contaminant within vadose zone environments. A contaminant can occupy one or multiple phases and the rate of transport within each of these phases can vary in both direction and magnitude. Contaminant transport is further complicated by the interaction between the phases and the chemical processes that occur in each phase. Care must be taken to incorporate all of the processes involved in contaminant transport within vadose zone environments.

C4. VADOSE ZONE GEOCHEMICAL CONCEPTUAL MODEL

As water moves through the soil matrix, reactions transfer dissolved constituents between solution (aqueous phase) and solid, vapor, and biological phases. Biogeochemical reactions can significantly alter the rate at which contaminants move relative to the rate at which water moves. These phase transfers generally retard the rate of contaminant movement; however, transfers to the vapor phase (^{14}C, tritium, and volatile organic compounds) can increase the rate of migration.

C4.1 Biogeochemical Processes

The important processes in biogeochemistry are surface adsorption, dissolution – precipitation, oxidation – reduction, complexation, volatilization, and biotransformation. Biogeochemical reactions are described by the law of mass action that indicates that chemicals react in definite proportions and that matter is conserved during reactions. The applicability of the law of mass action to a wide range of biogeochemical reactions is illustrated by the decrease in uranly ion ($UO2^{+2}$) adsorption above a pH of 8 (Figure C-11) as a side effect of the decomposition of organic matter by microbes.

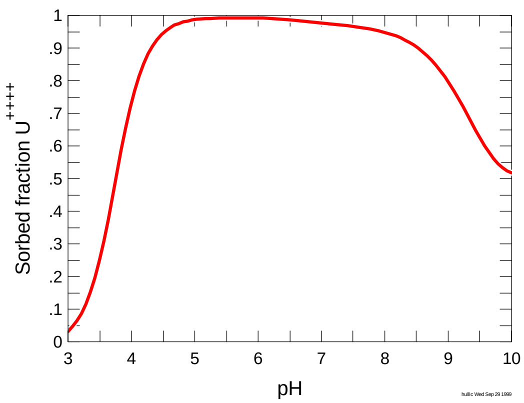


Figure C-11. Fraction of uranium adsorbed from solution as a function of pH. At low pH, hydrogen ion competes for exchange sites with uranyl. At high pH, carbonate complexing with uranyl inhibits adsorption. $\Sigma U = 10^{-6}$ molar, $\Sigma C = 10^{-3}$ molar.

Microbes oxidize organic matter [CH_2O] to water [H_2O] and carbon dioxide [CO_2] using dissolved oxygen [O_2] and releasing energy that the microbes use to live.

$$CH_2O + O_2(aq) \xrightarrow[\text{microbes}]{} CO_2(aq) + H_2O$$

$$O_2(g) \longleftrightarrow O_2(aq)$$

$$CO_2(aq) \longleftrightarrow CO_2(g)$$

Oxygen is dissolved from the vadose zone vapor phase and carbon dioxide released to the vapor phase to compensate for the changes in aqueous concentrations from the reaction. The presence of a vapor phase is important to this reaction, and so vadose zone biogeochemical activity is tied to hydrology as the water content controls the gas-filled porosity and the transport of nutrients. If the rate of oxygen consumption exceeds the rate of oxygen replenishment, reducing conditions will develop. Under reducing conditions, microbes can use other electron receptors to survive.

Carbon dioxide in the vadose zone reacts with water to form carbonic acid [H_2CO_3]. Carbonic acid reacts with soil minerals such as calcite [$CaCO_3$ (s)], dissolving the minerals and releasing solutes to the aqueous phase.

$$CO_2(aq) + H_2O \longleftrightarrow H_2CO_3$$

$$CaCO_3(s) + H_2CO_3 \longleftrightarrow Ca^{+2} + 2HCO_3^-$$

Some of these reactions are reversible, and when vadose zone water is lost by evapotranspiration, minerals can precipitate from solution.

The dissolution of minerals by carbonic acid consumes hydrogen ion, raising the pH, and increases the concentration of dissolved carbonate $[HCO_3^-]$. Dissolved carbonate forms aqueous complexes with metals such as uranyl $[UO_2^{+2}]$. Geochemical reactions depend on the concentration of the free ions in solution. As carbonate complexes the uranyl ion, the concentration of free ion in solution decreases, though the total amount of uranium in solution remains the same:

$$UO_2^{+2} + nHCO_3^- \longleftrightarrow UO_2(CO_3)_n^{-2(n-1)} + nH^+$$

$$UO_2^{+2} + \equiv SOH^0 \longleftrightarrow \equiv SOUO_2^+ + H^+$$

By decreasing the free uranyl concentration in solution, carbonate complexing decreases the amount of uranyl that can be removed by forming surface complexes on mineral adsorption sites in the soil $[\equiv SOH^0]$.

Uranium buried in waste can be present in a variety of forms. Frequently, metallic uranium has been oxidized to uraninite (UO_2) or U_3O_8 prior to disposal at the Subsurface Disposal Area. Uranium oxides are not stable in oxidizing conditions in contact with water with respect to uranium hydroxide (Schoepite) (see Figure C-12), and hydration reactions will occur in the waste.

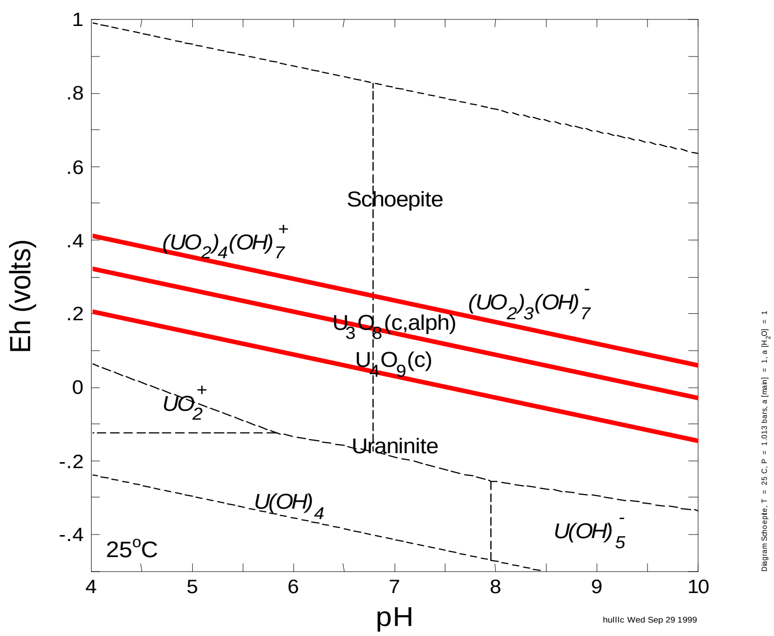


Figure C-12. Eh-pH diagram of uranium stability relations. Italicized text indicates aqueous species, standard text indicates solid phases, dotted lines separate stability fields for aqueous species, and solid lines separate stability fields of solid phases. The upper diagonal dashed line represents the upper boundary of the stability field of water.

In oxidizing conditions, the concentration of free uranium in solution is controlled by Schoepite mineral solubility. The concentration of uranium in solution is on the order of 10^{-6} to 10^{-5} molar at a neutral pH (see Figure C-13). If microbial action depletes the dissolved oxygen in the waste and conditions become reducing, then Schoepite will not be stable relative to the oxides, and uraninite is likely to control the concentration of uranium in solution. Under reducing conditions, the concentration of uranium in solution in equilibrium with uraninite will be lower than 10^{-8} molar (see Figure C-14). Where the solubility of a uranium mineral phase controls the concentration of uranium in leachate migrating from a waste, reducing conditions in the waste will result in a two order of magnitude decrease in the release of uranium from the waste.

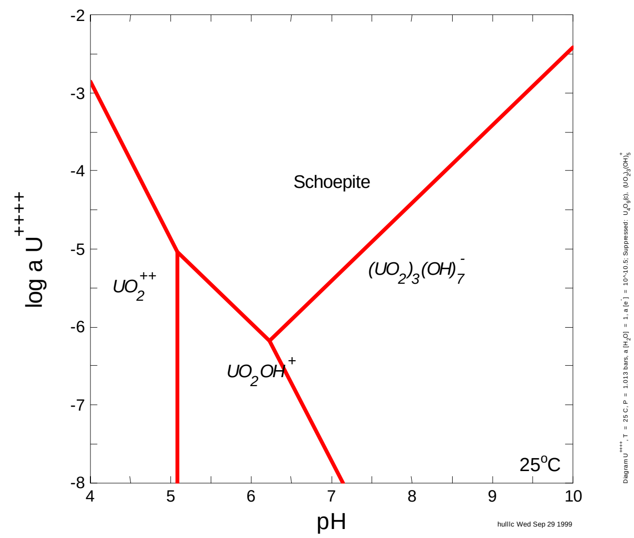


Figure C-13. Solubility of uranium in solution in equilibrium with Schoepite under oxidizing conditions.

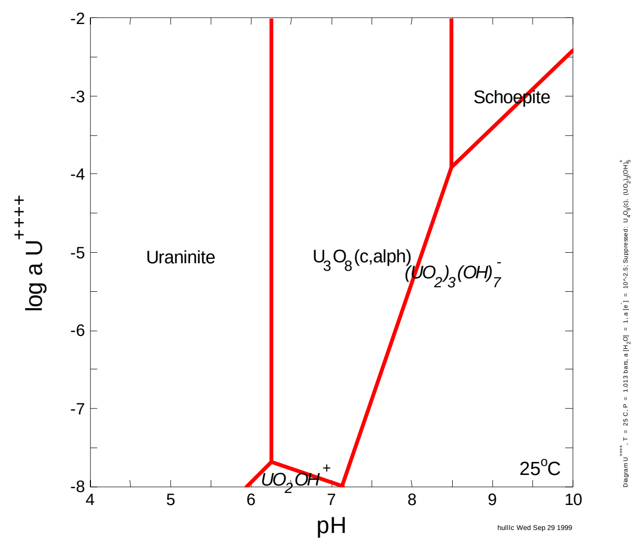


Figure C-14. Solubility of uranium in solution in equilibrium with uraninite and U_3O_8 under reducing conditions.

$$U_3O_8 + \tfrac{1}{2}O_2 + 9H_2O \longleftrightarrow 3\,UO_2(OH)_2 \bullet 2H_2O \quad (\textit{Schoepite})$$

C4.2 Mineral and Solution Equilibria

Thermodynamic data to describe equilibrium between species in solution and between solutions and solid mineral phases are reasonably well developed, even for actinide radionuclides (Grenthe et al. 1992; Silva et al. 1995; Spahiu and Bruno 1995). The aqueous model describes the interaction of inorganic and organic chemicals in aqueous solution. The aqueous model calculates the activities of species in solution and the reactions between solution and inorganic chemicals.

C4.2.1 Speciation Model

The most common aqueous geochemical model is a chemical speciation model where ions in solution are speciated based on an ion pairing model (Serne, Arthur, and Krupka 1990; Steefel and MacQuarrie 1996; Lieser 1995). Ion activities are determined using the Debeye-Huckel or Davies equations. These equations limit the model applicability to relatively low ionic strength solutions. The model could be extended to higher ionic strengths using the Pitzer equations (Harvie, Moller, and Weare 1984; Suarez and Simunek 1996, 1997). For soil waters in an arid environment, or for waste disposal situations, the ability to model high ionic strength solutions could be advantageous. The availability of data for the Pitzer equations for heavy metals and radionuclides is not known and the availability of thermodynamic data may significantly hinder the implementation of Pitzer equations.

C4.2.2 Equilibrium Processes

For geochemical reactions that are rapid and reversible, an equilibrium model is used. Chemical reactions that take place within the aqueous phase usually occur quickly enough that equilibrium is maintained (Morel 1983). For other reactions, the rate of reaction must be compared to the time scale of interest. Often partial equilibrium models or pseudoequilibrium models are acceptable. To be able to predict biogeochemical changes with time in a soil-water system, however, a kinetic description of biogeochemical reactions is needed.

C4.2.3 Redox

Oxidation-reduction reactions are driven by microorganisms. The reactions microorganisms use for energy must be thermodynamically favorable (Chapelle 1993). This depends on the geochemical environment of the subsurface. Electron exchanges between redox pairs will be driven by the availability of food and substrate. There are a few inorganic redox reactions, such as oxidation of ferrous iron by ferric iron, that are likely to occur (Scharer et al. 1993). There should be a very close link between the biological degradation model and the inorganic solution model because all components will have to be conserved across both types of reactions (Yeh and Salvage 1997; McNab and Narasimhan 1994, 1995; Humphreys et al. 1995). This suggests that setting up the biological reactions and the inorganic reactions in the same form and solving together with the same algorithm is the most efficient way to run the model.

C4.3 Adsorption on Mineral Surfaces

Over a number of years, a theoretical basis for describing adsorption reactions onto mineral surfaces has been developed. An extensive base of experimental data on the adsorption of metals and anions onto single minerals in laboratory experiments is available. However, this approach has not been extended to deal with mixtures of minerals or to natural vadose zone materials. This application of mechanistic adsorption to natural materials is currently the largest gap in our ability to model the migration of contaminants in the environment.

The K_d approach provides an empirical description of the retardation of a contaminant moving with groundwater. Mechanistic models have been developed to describe the adsorption process (Appelo 1996; Appelo and Postma 1996; Davis and Kent 1990; Dzombak and Morel 1990). While these mechanistic models have not yet been widely applied in radioactive waste site assessments, applications are being developed for Yucca Mountain (Triay et al. 1997) and the Nuclear Regulatory Commission (Kent et al. 1988). The empirical K_d approach cannot address the effects of large pH changes during neutralization of waste solutions or changes in solution composition as high ionic strength waste solutions are diluted. The mechanistic models can explicitly account for changes in solution chemistry. On the other hand, the mechanistic models are computationally very intensive, and are not suitable for complex three-dimensional transport simulations. Therefore, mechanistic models and geochemical codes can be used to model the release and transport of contaminants near the source where solution chemistry is changing rapidly. Mechanistic models and geochemical codes can be used to calculate K_d values for use in the fate and transport code away from the source where solution chemistry is stable.

Mechanistic models describe interactions between aqueous species and mineral surfaces that occur through electrostatic and covalent bonds. Ion exchange reactions are primarily electrostatic and depend on the attraction between negatively charged mineral surfaces and cations in solution. Surface complexes form a covalent chemical bond between a site on the mineral surface and an ion, and can form even when the surface and the ion have opposite charges.

C4.3.1 Ion Exchange

Clay minerals are the most common ion exchange media in soil and develop a fixed, negative surface charge by lattice substitution of trivalent cations for silica (Al^{+3} for Si^{+4}) in tetrahedral sites and substitution of divalent cations for aluminum (Mg^{+2} for Al^{+3}) in octahedral sites. The negative charge is balanced by attracting cations from solution to the surface of the clay. Exchange sites on clays are preferentially filled by ions with higher charge density (small hydrated size, large charge). Some ions that are themselves fairly small (lithium, sodium) are hydrated, and the hydrated ion is larger than some of the larger cations (cesium, strontium). The order of preference for ion exchange depends primarily on ionic properties, not clay properties. The clay determines the total capacity, but the preference depends on the ion. The general order of selectivity for exchange sites for divalent cations is (Deutsch 1997)

$$Pb^{+2} > Ba^{+2} \approx Sr^{+2} > Cd^{+2} \approx Zn^{+2} \approx Ca^{+2} > Mg^{+2} \approx Ni^{+2} \approx Cu^{+2} > Mn^{+2} > Fe^{+2} \approx Co^{+2}.$$

Divalent cations have a greater selectivity than monovalent cations.

An ion exchange reaction is written as a mass-balance chemical reaction:

$$Na^{+} + 1/2CaX_2 \leftrightarrow 1/2Ca^{+2} + NaX$$

with

$$K_{Na/Ca} = \frac{[NaX][Ca^{+2}]^{0.5}}{[CaX_2]^{0.5}[Na]^{+}}$$

where

X = Cation exchange site concentration (moles/L)

$K_{Na/Ca}$ = Selectivity coefficient for sodium – calcium exchange.

Ion exchange reactions are written as if all the exchange sites were filled at all times. The exchange coefficients, therefore, represent the relative strength of the ion exchange reaction. Selectivity coefficients have been determined and are published in the literature (Appelo and Postma 1996). These coefficients are not thermodynamic equilibrium coefficients. Site-specific data are needed to develop selectivity coefficients for INEEL materials. An ion exchange approach was successfully used to model strontium-90 migration in the presence of competing cations for a glacial outwash aquifer (Kipp, Stollenwerk, and Grove 1986).

Because strontium is one of the most preferred cations for ion exchange, it will compete successfully with other cations for exchange sites. Hydrogen ion is hydrated, and has a fairly low charge density. As a result, hydrogen ions do not compete well for exchange sites. Using the selectivity coefficients determined for INEEL soils, and ion exchange theory, the effects of low pH and competing cations can be explicitly included in a calculation of strontium adsorption.

C4.3.2 Surface Complexation

Surface complexation is the formation of a chemical bond between an ion and a reactive surface site on a mineral surface. There are several levels of complexity in mechanistic surface complexation models. At the simplest level, a mineral surface can have a surface charge that depends on the pH of solution. The surface hydroxide groups on the mineral surface act as a diprotic acid and can gain or loose hydrogen ions:

$$\equiv SOH_2^+ \leftrightarrow \equiv SOH^0 + H^+$$

$$K_{a1} = \frac{[\equiv SOH^0][H^+]}{[\equiv SOH_2^+]}$$

$$\equiv SOH^0 \leftrightarrow \equiv SO^- + H^+$$

$$K_{a2} = \frac{[\equiv SO^-][H^+]}{[\equiv SOH^0]}$$

where

$\equiv SOH^0$ = Surface hydroxide group on a soil oxide mineral (moles/L)

K_{a1}; K_{a2} = Apparent acidity constants.

The mineral surface can have a positive, neutral, or negative charge depending on solution pH. The equilibrium constants for gain and loss of a proton (K_{a1} and K_{a2}) have been measured for soil oxide phases such as FeOOH, AlOOH, and SiO_2.

Cations in solution form complexes with the surface site as described by a chemical mass-balance reaction:

$$\equiv SOH^{0} + M^{+m} \leftrightarrow \equiv SOM^{+(m-1)} + H^{+}$$

$$K_i = \frac{[\equiv SOM^{+(m-1)}][H^{+}]}{[\equiv SOH^{0}][M^{+m}]}$$

where

K_i = intrinsic equilibrium constant for adsorption.

This reaction releases a hydrogen ion into solution, and so the equilibrium between the free metal in solution and the adsorbed metal on the surface will depend on pH. At low pH, the metal may not be able to replace a hydrogen ion on the surface, and adsorption will be decreased (see Figure C-11). The adsorption equation is written in terms of the concentration of the free metal in solution. If complexing agents are present in solution, they will take some of the free metal ion and sequester it in solution in the form of a complex. The complexed metal is “hidden” from the surface reaction, and does not take part in the formation of the surface complex. This simple mechanistic approach can address pH effects and solution chemistry effects on adsorption of metals onto minerals. It has been applied to laboratory studies (Kohler et al. 1996) and field investigations (Furrer, von Gunten, and Zobrist 1996; Kent et al. 1999; Kent and Maeder 1999). This approach would permit addressing the low pH of the waste solutions, complexing with organic chelating agents, and the formation of inorganic complexes with fluoride, phosphate, carbonate, or other ligands in solution.

C4.3.3 Modeling and Implementation

A surface complexation model should be used for solid phases where the surface charge is dependent on pH and ionic strength (Dzombak and Morel 1990). Surface complexation is a common module in geochemical codes (Parkhurst 1995; Allison, Brown, and Novo-Gradac 1991; Serne, Arthur, and Krupka 1990). Surface complexation modeling is less commonly implemented in reactive transport codes (Yeh and Salvage 1997). Implementation of surface complexation depends on development of a partition coefficient between the aqueous activity and the surface activity of species. Because surface oxy-hydroxide sites have such a range of site energies, a single partition coefficient does not describe the solution-surface interaction well. A number of papers have addressed the development of coefficients to describe surface complexation reactions in complex soil systems with multiple sites (Westall et al. 1995; Cernik, Borkovec, and Westall 1995). This is an area that requires additional investigation, but one that could have significant benefits to predictive modeling of radionuclides and heavy metals.

C4.4 Mineralogy

Adsorption is a surface phenomenon and depends on mineral surfaces. The mineralogy of sediments and basalts has been investigated at the INEEL. The mineralogy of the Big Lost River alluvium is quartz (32 to 45%), plagioclase feldspar (16 to 30%), clay minerals (8 to 14%), potassium feldspar (6 to 18%), pyroxene (8 to 14%), and calcite or dolomite or both (2 to 6%) (Bartholomay 1990). The clay minerals identified in the alluvium are illite, smectite, mixed-layer illite-smectite, kaolinite, and chlorite. The clay minerals are detrital and have not formed in place by weathering (Knobel, Bartholomay, and Orr 1997). At some locations, the gravel is lightly cemented or coated by secondary calcite. Analysis of coatings on the alluvium indicates that the composition is 45% silica, 45% calcite, 5% iron oxide, and 5% aluminum oxide (Nace et al. 1975).

The carbonate (calcite and dolomite) grains and coatings provide rapid acid neutralization and pH buffer capacity, as well as ion exchange sites for strontium. The clay minerals provide sites for adsorption of cationic contaminant species such as Sr^{+2} and PuO_2^{+2}, and the iron and aluminum oxide coatings provide a range of sites having positive, negative, and neutral charges. At very low pH (i.e., pH of less than 3), the surfaces of oxides are positively charged, and cation adsorption reactions are inhibited. As the pH of solution rises, cation adsorption increases significantly in the pH range of 4 to 6. Oxide coatings also provide sites for adsorption of both cations and anionic contaminant species such as $PuO_2(CO_3)_2^{-2}$.

Beneath the surficial alluvium lie 600 to 900 m (2,000 to 3,000 ft) of layered basalt flows and interbedded sediments (Nace et al 1975). The basalt flows are characterized as overlapping lobes of basalt intermixed with larger basalt flows of relatively uniform thickness beneath the INTEC. The sediments found between the basalt flows are often discontinuous and characterized by sequences of sand, silt, clay, and lesser amounts of gravel (Mundorf, Crosthwaite, and Kilburn 1964).

A number of studies of basalt mineralogy are summarized by Knobel, Bartholomay, and Orr (1997). Key findings of these studies are that the mineralogy of the Snake River Plain basalt is remarkably uniform in composition, and that very little weathering of basalt is noted in this section. Fractures and vesicles in basalt can contain sediments washed into the basalt after cooling. These sediments are generally fine-grained silt- and clay-sized particles consisting of quartz and clay minerals with lesser amounts of feldspar, calcite, and pyroxene.

The sedimentary interbeds are primarily composed of sand and silt, with some small clay lenses. The majority of the interbeds are thin (0.3 to 1.5 m [1 to 5 ft]) layers of silt that were deposited in eolian or fluvial environments between the major basalt flows. The mineralogy of the interbeds is similar to the alluvium, with the composition of quartz (18 to 39%), plagioclase and potassium feldspar (26 to 42%), clay minerals (0 to 42%), and pyroxene (0 to 41%). Dolomite is absent and calcite is variable (0 to 28%). Identified clay minerals include illite, smectite, mixed-layer illite-smectite, kaolinite, and chlorite (Knobel, Bartholomay, and Orr 1997). Clay minerals were identified as detrital and commonly have reddish coatings of ferric oxyhydroxides (Rightmire 1984; Rightmire and Lewis 1987).

Clay and iron oxide minerals provide the greatest amount of radionuclide retardation within the interbed portion of the groundwater flow path. A complication, however, is that the percentage of these minerals spatially varies, as does the thickness of the interbeds. Multiple pathways exist for water infiltrating through the vadose zone because infiltrating water may be deflected and move laterally along an interbed for some distance before resuming a vertical path. The actual distance traversed by infiltrating water through the interbeds and the amount of sorptive surfaces encountered by infiltrating water within the interbeds are not accurately predictable.

C4.5 Reaction Kinetics

For geochemical reactions that are rapid and reversible, equilibrium among reactants can be assumed. Chemical reactions that take place within the aqueous phase usually occur quickly enough that equilibrium is maintained. For other reactions, the rate of reaction must be compared to the time scale of interest. Often partial equilibrium models or pseudoequilibrium models are acceptable. For geochemical reactions that are slow or irreversible, data for a kinetic model are needed. Kinetic processes have been incorporated into a number of geochemical transport and reaction codes (Lichtner 1996; Suarez and Simunek 1996, 1997; Yeh and Salvage 1997). Generally, these codes deal with a carefully selected set of potential geochemical reactions to study well-defined systems. Lichtner (1996) modeled weathering of silicate rocks and Suarez and Simunek (1996, 1997) modeled the system calcium-carbonate-sulfate in soils under irrigated agriculture. When dealing with well-constrained systems, a kinetic approach can be successfully applied. Generally, kinetic data that can be applied to field conditions are lacking for inorganic geochemical systems (Morel 1983). The many variables present in soil environments are not usually addressed in laboratory kinetic investigations.

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Appendix D

Section 3, of “Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory (Draft)”

Appendix D

Section 3, of "Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory (Draft)"

D3. GROUPED DEFICIENCIES IN VADOSE ZONE UNDERSTANDING

The deficiencies and associated recommendations described in this section were developed and should be viewed within the context of the conceptual models outlined in Appendix C. The conceptual models that have been developed at the INEEL describe the geologic framework, the hydrologic environment, the transport mechanisms causing contaminant movement, and the geochemical controls on transport mechanisms and represent the state of knowledge of the vadose zone and its geologic and hydrologic context at the INEEL. They are based on several decades of cumulative experience at the INEEL and on the state of scientific knowledge for each discipline.

Though the deficiencies and recommendations were developed specifically for vadose zone conditions at the INEEL, they are equally applicable to most vadose zone conditions, particularly fractured rock sites in arid and semiarid regions. Review of current literature and scientific interchanges between geoscientists at the INEEL and at other DOE sites show that the vadose zone problems faced at the INEEL are universal in nature (e.g., GAO 1998; Rousseau, Kwicklis, and Gillies 1997; Eaton et al. 1996). Throughout the DOE complex, similar problems occur with, for example, flow and transport modeling, monitoring, instrumentation, spatial variability and heterogeneity, geochemistry, microbiology, source terms, and contaminant vapor-phase transport.

The deficiencies identified in vadose zone understanding at the INEEL are grouped by subject area in the following subsections:

Section D3.1 Flow and Transport Modeling

Section D3.2 Hydraulic Monitoring and Sampling

Section D3.3 Vadose Zone Instrumentation

Section D3.4 Characterization of Scale and Spatial Heterogeneity and Preferential Flow

Section D3.5 Geochemistry

Section D3.6 Characterization of the Geologic Framework and Hydrologic Properties

Section D3.7 Geophysical Methods

Section D3.8 Microbiology

Section D3.9 Surface Covers

Section D3.10 Physics of Flow

Section D3.11 Source Term

Section D3.12 Contaminant Vapor-Phase Transport

Section D3.13 Integration.

D3.1 Flow and Transport Modeling

D3.1.1 Summary

Predictive simulation studies of subsurface contaminant flow and transport at the INEEL and elsewhere are required to enhance the level of understanding of the mechanisms controlling flow and transport and to answer regulatory concerns about vadose zone contamination problems. Vadose zone contaminant concentrations are a source to the Snake River Plain Aquifer. Simulation studies are used to estimate groundwater concentrations as a function of time at hypothetical receptor locations.

In general, the contaminant flow and transport simulation process consists of the following:

- Developing a conceptual model of the physical and chemical processes governing flow and transport.

- Developing or selecting the appropriate governing equations for those processes (embedded in a simulator).

- Discretizing a domain of interest.

- Assigning model parameters to describe flow and transport properties over the model domain.

- Assigning initial and boundary conditions.

- Performing simulations.

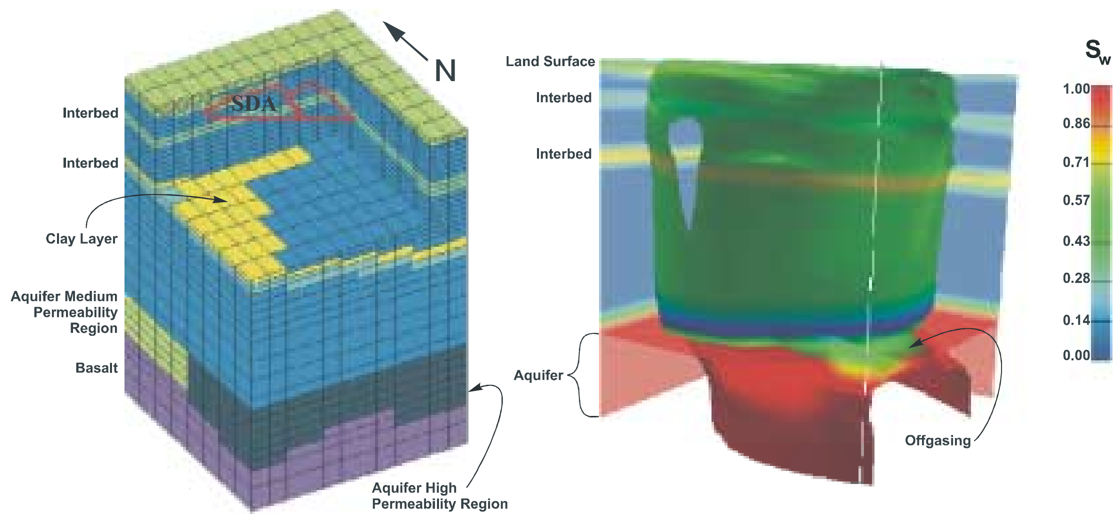
- Comparing simulation results to field observations, a process generally referred to as history matching.

- Making decisions about revising the conceptual model, governing equations, parameters, initial conditions, and boundary conditions to improve agreement between simulated conditions and observed monitoring results. The result is a simulation model.

- Using the simulation model to predict the movement and future concentrations of contaminants in the subsurface.

The simulation process helps to identify the factors that are understood about subsurface flow and transport from available hydrologic and contaminant monitoring data and likewise the factors that are not understood about these same data. It provides guidance for conducting activities to improve understanding and prediction capabilities. Figure D-1 shows an example application of flow and transport modeling.

The conceptual models that have been employed in simulation studies at the INEEL have almost exclusively relied on the concept that the subsurface, including the fractured basalt, can be simulated as some sort of equivalent continuum. Equivalent porous media, dual porosity, and dual permeability media have been used to represent the fractured basalt comprising the majority of the vadose zone. Processes



Cutaway view of Subsurface Disposal Area three dimensional grid with lithologic implementation.

Flow and transport simulation results showing carbon tetrachloride isosurface with water saturation superimposed.

Figure D-1. Flow and transport modeling results showing an isosurface of carbon tetrachloride aqueous-phase concentrations in both the vadose zone and the underlying aquifer with water saturation superimposed

and parameters used in the simulation process are developed from a variety of sources. Though these are best developed from an understanding based on field observations, literature values and conservative estimates also are often used. The equivalent continuum approach is consistent with modeling studies performed across the DOE complex, including those conducted at the Yucca Mountain DOE site in Nevada (Pruess, Faybishenko, and Bodvarsson 1999). As at the INEEL, variably saturated flow and contaminant transport in porous fractured media are a primary concern at the Yucca Mountain site.

A primary goal in the simulation process is the creation of numerical models that accurately represent contaminant transport at a facility. This goal has not been achieved at most INEEL facilities. The next section highlights current deficiencies in conducting simulation studies.

D3.1.1 Deficiencies

The primary deficiencies that affect the ability to conduct representative simulations of subsurface flow and transport in the vadose zone at the INEEL are listed below:

Field obtained data sets of sufficient quality for use in modeling are limited. The available field data often are inconsistent, showing transport at one location and not at others. These types of data do not provide a consistent spatial or temporal trend that can then be used in the model calibration process. Extreme preferential flow (i.e., where water bypasses the majority of the subsurface medium) probably occurs in some of these situations. Preferential flow is difficult to represent in existing models, which suggests that more appropriate models are required.

- The lack of a definitive mechanism for describing water movement through the unsaturated fractured basalts limits the ability to represent flow and transport in the vadose zone. Currently, an equivalent porous media approach is used that incorporates Richard's equation (1931) even though there is no demonstrated basis that the approach is correct.

- Uncertainty in mechanisms of fracture-matrix interactions limits the representativeness of simulations of flow and transport in the vadose zone. Limited representativeness particularly applies to contaminants such as volatile organics with a significant component that migrates via vapor phase flow. Determining the extent to which these contaminants have migrated into the basalt matrix from the fractures and the amount of time it will take for them to diffuse back out is an unsolved remediation problem.

- The nonlinear governing equations for multiphase flow require iterative solution schemes. The low computational efficiency of current simulators limits the amount of discretization that can be included in vadose zone simulations. The inability to incorporate spatial variability in lithology and hydrologic and transport properties at the scale at which it can be observed requires making parameter estimates and assignments on the scale of the minimum-achievable model discretization.

- Simulation studies of contaminant transport in the vadose zone have been primarily based on dissolved-phase transport with equilibrium linear reversible adsorption. This approach cannot simulate facilitated transport mechanisms. Facilitated transport mechanisms are not well understood.

- The simulation studies that have been conducted have been primarily deterministic with only limited attempts at including uncertainty. Uncertainty in hydrologic parameters (e.g., permeability and moisture characteristic curves) and in boundary conditions (e.g., infiltration magnitude, timing, and spatial variability) affects the usability of the simulation results for making environmental decisions.

- A programmatic limitation affecting simulations of flow and transport in the vadose zone at the INEEL arises from the tendency of DOE and regulatory staff to prefer use of a particular simulation code, notwithstanding the characteristics of the system. For example, the most recent introduction of the TETRAD simulator required a year to obtain concurrence from DOE, the U.S. Environmental Protection Agency (EPA), and the Idaho Department of Health and Welfare (IDHW) that the code was usable for simulation studies of Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites. Any attempts to consider use of alternative simulation codes since then have been met with great reluctance because of the amount of time potentially required to obtain additional approval.

D3.1.2 Recommendations

- In terms of simulation capability, develop computationally efficient simulators to allow the discretization necessary to represent flow and transport in the complex and heterogeneous vadose zone at the INEEL. These simulators need to be able to include the following:

  - Kinetic reactive transport

  - Facilitated transport

  - Dual-porosity, dual-permeability media

  - Efficient visual post-processing

  - Geostatistically based input of spatially varying properties, with explicit accounting and aggregation of uncertainties

  - Inverse parameter estimation techniques

  - Alternative conceptual models to equivalent continuum descriptions of water and contaminant movement in fractured basalt and sedimentary interbeds.

  Not all of these features will be found in a single simulation code. Rather, portions of the necessary features will be found in a variety of codes that have been developed already, and other features will be included in codes that are still in development.

- Develop improved data sets obtained at more closely spaced spatial intervals and over long time periods.

- Establish a process for facilitated approval and adoption of improved simulation codes for use at the INEEL.

D3.2 Hydraulic Monitoring and Sampling

D3.2.1 Summary

Monitoring and sampling for laboratory determinations of hydraulic parameters have been conducted primarily in response to Environmental Restoration and Waste Management Program requirements for individual projects at various INEEL sites. The project requirements were developed in response to contaminant fate and transport modeling needs to meet specific regulatory milestones. Because the investigations are project driven, they tend to be of short duration over localized geographical areas. Project needs also have largely dictated the selection of monitoring and sampling parameters. Generally, the variables monitored in the field were moisture content, matric potential, perched water levels, and soil temperature. Laboratory determined hydraulic parameters included moisture content, porosity, bulk density, moisture characteristic curves, saturated hydraulic conductivity, and particle size analyses. The monitoring and sampling have focused on the surficial sediments, though some instrumentation has been installed to monitor the basalt and interbeds, and a few samples have been collected from these materials. Vadose zone hydraulic investigations are described in detail in Appendices A and B.

D3.2.2 Deficiencies

Though the investigations sited above have generated much useful hydraulic data that have been valuable in understanding the hydraulic processes occurring in the INEEL vadose zone, deficiencies are associated with the data. These deficiencies are discussed below.

D3.2.2.1 Limited Applicability of Data—The applicability of facility-specific data to other INEEL facilities is questionable because of the INEEL site's spatial variability.

The INEEL is heterogeneous relative to the surficial alluvium, the fractured basalts, and the sedimentary interbeds (see Section 3.4). This heterogeneity introduces uncertainty when using data collected at one facility to characterize similar processes at another. For instance, the most comprehensive hydraulic monitoring and sampling occurred at the Radioactive Waste Management Complex (RWMC). A large data set was collected that is believed to be spatially representative of the Subsurface Disposal Area (SDA) and perhaps other INEEL sites with similar surficial sediments. However, several miles north of the SDA, the Idaho Nuclear Technology and Engineering Center (INTEC) is located near the Big Lost River. There the surficial sediments are alluvial in nature rather than the silty clay found at the SDA. Only limited monitoring and sampling for hydraulic processes have been undertaken in the INTEC alluvium even though the hydrologic behavior of this material is likely to differ significantly from that at the SDA. The range in unsaturated hydraulic properties and the spatial distribution has not been defined or measured for the INEEL.

D3.2.2.2 Discontinuity of Monitoring—Project-specific funding without an over arching Environmental Restoration or Waste Management Program directive has led to relatively short-term, discontinuous monitoring, which adds uncertainty to the quantification of hydrologic data required for making long-term predictions of contaminant mobility.

Project constraints and shifting priorities under changing management rather than science sometimes limit the continuity of long-term monitoring programs. For example, moisture monitoring data were collected from 1986 through 1990 at the RWMC. In the fall of 1990, funding for RWMC monitoring was withdrawn, monitoring was revived in 1993, and the monitoring network expanded in 1994. Monitoring of the expanded network was conducted for three years until the funding was again curtailed at the end of 1996. Though the monitoring resulted in a large data set, the data are probably not representative temporally because of the gaps and short duration in the hydrologic data sets. These gaps are important because snowfall, the form of precipitation that generally has the greatest impact on infiltration at the SDA, varies from year to year. Some years are wet, while most are dry. In a statistical analysis focusing on total snowfall, Dehaan[1] showed that monitoring had to be continuous over an 8 year period to have a 90% chance of collecting data from a "wet" year. Data from a "wet" year are important because they provide an upper range for the quantification of infiltration.

But snowfall is only one of the important inputs to infiltration and perched water development, another is the snow melt process itself. For example, if the spring melt occurs over frozen ground, the melt water redistributes to low areas and forms ponds. When the ground thaws under the ponds, most of the ponded water infiltrates (during February evapotranspiration rates are low), which can result in larger volumes of water moving through the vadose zone in a few small areas.

If these two parameters are combined, the chance of monitoring during a "wet" year requires monitoring for more than the 8 years that Dehaan predicted. Monitoring has not been of sufficient duration to capture the effects of ponding and focused infiltration during cycles of large snowfalls. Figure D-2 shows ponding at the SDA that resulted from an average snow melt over frozen ground.

D3.2.2.3 Limited Monitoring and Sampling—Monitoring and sampling for hydrologic property determination has been performed in some but not all the media types encountered at INEEL facilities.

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1. Dahaan, M. S., 1999, Interdepartmental Communication to C. W. Bishop, Lockheed Martin Idaho Technologies Company.

The earlier discussion centered on moisture content and matric potential monitoring in the surficial materials (corresponding to the most significant data set that exists for the INEEL hydraulic monitoring). Relatively little information has been collected for the basalts and sedimentary interbeds, two of the important subsurface controls on moisture movement and, consequently, contaminant transport.

D3.2.2.4 Lack of Monitoring of Preferred Pathways—Most monitoring has focused on the matrix media with little attention given to preferred pathways where most of the moisture movement and contaminant transport occurs.

Figure D-2. Photograph showing ponding at the Subsurface Disposal Area resulting from an average snow melt over frozen ground.

The heterogeneity encountered at the INEEL results in part from the mixing of the sediments and the layered basalts, but more importantly, from preferred pathways in the vadose zone such as fractures, interbeds, rubble zones, and alluvial zones in the silty clay materials. Some monitoring and sampling information exists for matrix properties but, in general, information is lacking about hydraulic processes occurring in the preferred pathways. This deficiency results from the current inability to monitor these locations with existing technology.

D3.2.3 Recommendations

The following monitoring and hydraulic analytical activities are recommended to provide adequate monitoring and sampling of hydraulic data:

- Develop a process to determine what is enough data to calibrate and validate transport models.
- Determine what are sufficient monitoring data quality needs (prior to collecting data).
- Develop a monitoring network that is spatially representative of INEEL facilities.
- Collect data for a sufficiently long time to obtain a temporally representative data set.
- Develop a consistent set of monitoring parameters that will serve as basic monitoring parameters.

- Develop better monitoring instrumentation to permit monitoring in the preferred pathways such as fractures, interbeds, rubble zones in the basalts and alluvial zones in the silty clay materials (i.e., interbeds and surficial sediments). Better monitoring instrumentation also should be developed to efficiently monitor a larger scale, giving information that represents the general vadose zone.

- Standardize monitoring instrumentation, installation, calibration, and data collection (to the extent possible) and adjust calibrations for scale.

- Monitor remediated sites to verify modeling and remediation effectiveness.

- Determine what constitutes the appropriate number and sample size for a representative sample collection, especially at depth.

- Develop moisture characteristic curves for semi-dense and dense basalts and for gravel.

- Conduct relatively large-scale natural gradient tracer tests to determine the large-scale effects of preferential pathways.

D3.3 Vadose Zone Instrumentation

D3.3.1 Summary

Parameter estimation of transport properties is limited in part because of inadequate vadose zone instrumentation.

In general, vadose zone instrumentation is necessary to provide transport parameters for model predictions and monitoring data to describe the extent of contaminant migration as a function of time. Typically, vadose zone instruments are used to analyze the vadose zone matrix for state variables such as moisture content, water potential, temperature, and contaminant concentration dissolved in the pore water, in the subsurface gas, and sorbed onto the solid phases. These instruments measure the desired variable directly or indirectly by measuring a property of the parameter of interest. For example, water potential is measured directly using a tensiometer or indirectly using a thermocouple psychrometer. Instruments that measure the variable indirectly must be calibrated to the parameter to achieve an accurate measurement. An instrumentation package developed at the INEEL for vadose measurement and deployed at the Savannah River Site (Sisson and Hubbell 1998) is illustrated in Figure D-3. By combining numerous instruments together into one package, much more information is exploited from a single borehole.

A number of vadose zone instrumentation types have been used to monitor numerous vadose zone variables at the INEEL (Hubbell and Sisson 1998, 1996; Sisson and Hubbell 1999). To provide an overview of the status of instrumentation at the INEEL, a list is provided in Table D-1 of parameters measured at the INEEL, the instrumentation used to make these measurements, and the locations from which the measurements were made.

Measurements of water potential at several sites indicated that fast preferential flow can be detected using monitoring instruments and that flow through interbeds can impede moisture movement (Sisson and Hubbell 1999; Hubbell and Sisson 1998). This information assisted in developing the conceptual models of flow in the vadose zone.

Examples of in situ field data derived from the INEEL-developed Advanced Tensiometer are shown in Figures 3-4 and 3-5. The instrument provides direct evidence of flow characteristics in the

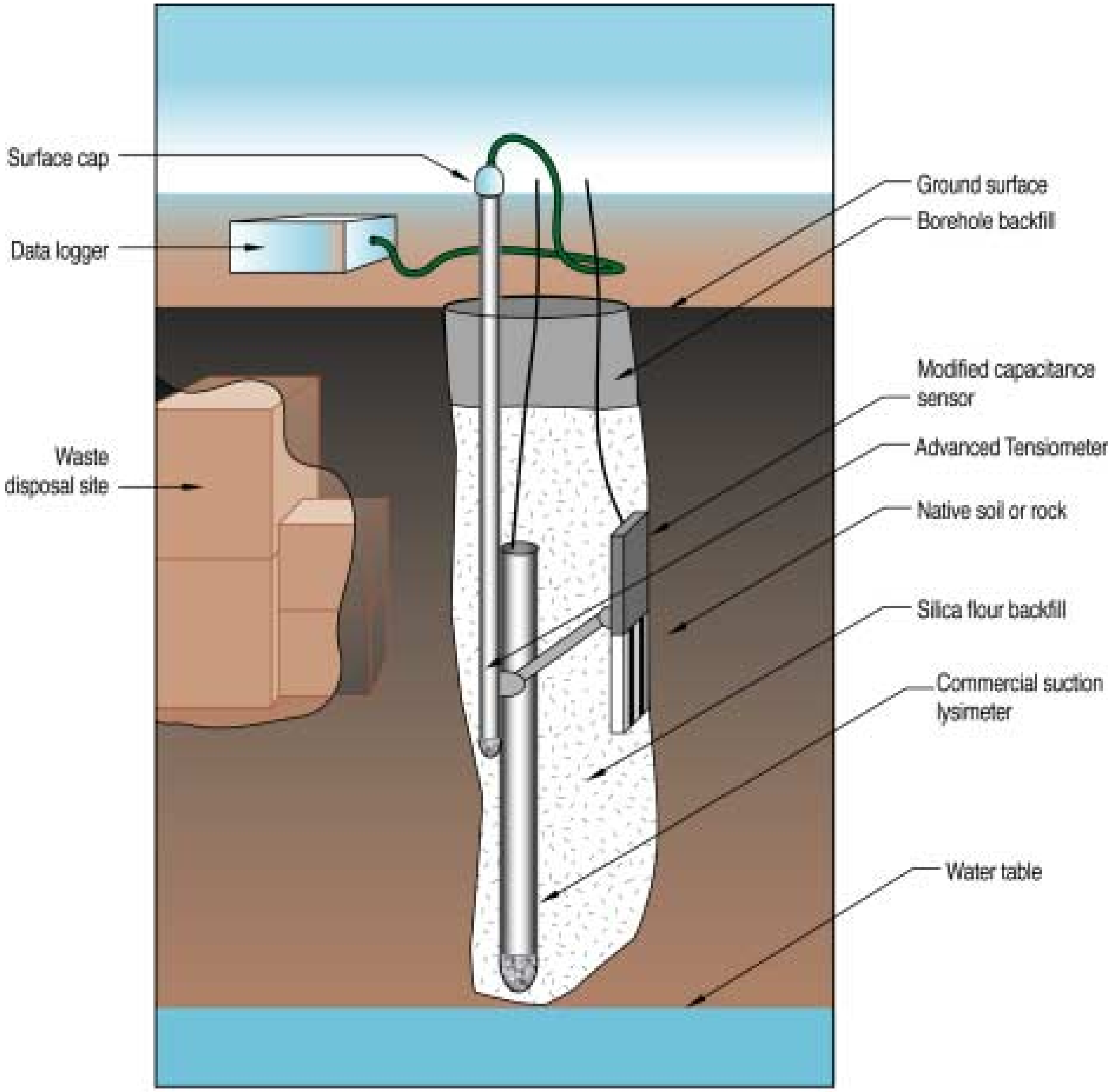

Figure D-3. INEEL-developed vadose zone instrumentation package.

Table D-1. Vadose zone parameters measured at the INEEL, the measurement instrument or method used, and the measurement locations.

Parameter	Instrument or Method	RWMC	INTEC	CFA	TRA	LSIT	Box Canyon	Hell's Half Acre	EBTF	USGS caisson	TAN	USGS GIN	Five-Well Site	Dairy Farm
		Measurement Location												
Moisture content	Neutron activation	√	√	√		√	√		√	√				√
	Gypsum blocks	√												
	TDR			√					√					
	Geophysical survey	√				√	√							
Water potential	Tensiometer	√	√				√	√	√	√			√	
	Heat dissipation blocks	√		√		√			√	√				
	Thermocouple psychrometers	√							√	√				
Chemical concentrations	Perched well monitoring	√	√		√	√								
	Suction lysimeters	√	√	√		√	√			√				
Water flux	Surface infiltration	√				√	√	√	√	√				√
	Perched water monitoring	√	√			√	√		√	√			√	√
	Drip counting							√						
Gas pressure	Gas ports with transducers	√										√	√	
Gas composition	Sampling of gas ports	√		√							√	√		
	Surface flux meters	√												
Temperature	Thermocouples								√					
	Thermistors	√		√			√	√						
Colloid concentrations	Suction lysimeters	√												
	Perched water sampling	√												

Acronyms

CFA	Central Facilities Area
EBTF	Engineered Barrier Test Facility
GIN	Gas injection
INTEC	Idaho Nuclear Technology and Engineering Center
LSIT	Large-scale infiltration test
RWMC	Radioactive Waste Management Complex
TAN	Test Area North
TDR	Time-domain reflectometry
TRA	Test Reactor Area
USGS	U.S. Geological Survey

basalt. In Figure D-4, changes are illustrated in the soil-water potential in response to fast infiltration of water through basalt in about 3 days from the 2.7-m depth to the 15.5-m depth. Saturated conditions form at the basalt/sediment interface at 2.7 m. The wetting front was detected in all of the underlying tensiometers. The timing of the first arrival of water in the instrument suggests that preferential flow is an important factor at this location. In Figure D-5, water is shown moving through sediment-filled fractures in basalt into the 9.4-m interbed at the RWMC. The flow rate of water through this interval is about 10 times lower than the example given above. Perched water was detected at the 22-ft depth in fractured basalt. The wetting front moved into and through the 30-ft interbed over a 40-day period.

D3.3.2 Deficiencies

- Modelers have identified source term mass flux in the vadose zone as the most sensitive input parameter to modeling results. Data are needed to provide ranges of the contaminant flux in an effort to allow more realistic modeling predictions. At present, no suitable instrumentation exists to directly quantify the contaminant flux beneath a contaminated site.

  Instrumentation currently is installed in the fractured basalt using methodology developed in the agricultural field for porous media. Review of downhole video logs has facilitated the depth placement of these instruments at fracture locations. However, the representativeness and potential bias of this method is unknown. The means by which the porous media backfill interacts with a fracture-matrix medium are unknown and the potential hysteretic effects involved are unquantified.

- As part of an ongoing project (see Table 2-1), colloids were measured in suction lysimeters beneath the Subsurface Disposal Area. It is unknown if the colloidal concentrations in these suction lysimeter samples actually represent the pore fluid in the vadose zone.

- Numerous organic contaminants have been detected in soil gas and groundwater samples. Biodegradation is likely occurring in these contaminated areas. Limited data on the biological activity exists, in part because of inadequate instrumentation.

- Spatial variability within the vadose zone at the INEEL has been poorly described because instrumentation typically measures only at borehole point locations. Numerical models need dense data sets to accurately predict contaminant transport. The spatial variability of state variables (e.g., moisture content, pressure head, and contaminant concentration) must be measured to estimate hydraulic properties for numerical transport models.

Often a soil or rock core is collected and brought into the laboratory to be analyzed for its properties. Ex situ (i.e., laboratory-scale) instrumentation has a long history of use and acceptance; however, this equipment generally measures properties at a scale too small (i.e., cores) to provide valid in situ parameters at the INEEL. For example, measuring the basalt-matrix permeability is of secondary importance if the fluid flow is primarily in the fractures. In situ equipment can have the ability to measure properties at a larger scale resulting in a more representative parameter measurement for the numerical modelers.

D3.3.3 Recommendations

The following instrumentation activities are recommended to significantly enhance understanding of vadose zone:

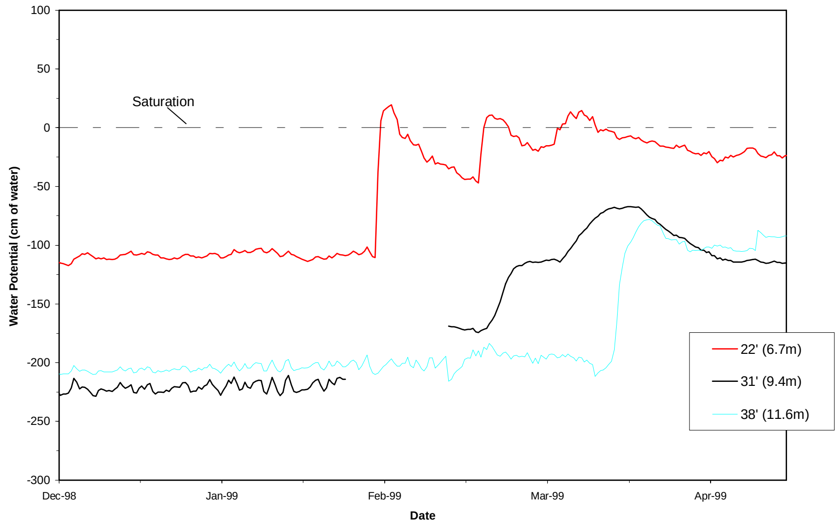

Figure D-4. Changes in the soil-water potential in response to fast infiltration of water through basalt in about 3 days from the 2.7-m depth to the 15.5-m depth. Saturated conditions formed at the basalt/sediment interface at 2.7 m. The wetting front was detected in all of the underlying tensiometers. The timing of the first arrival of water in the instruments suggests preferential flow is an important factor at this location.

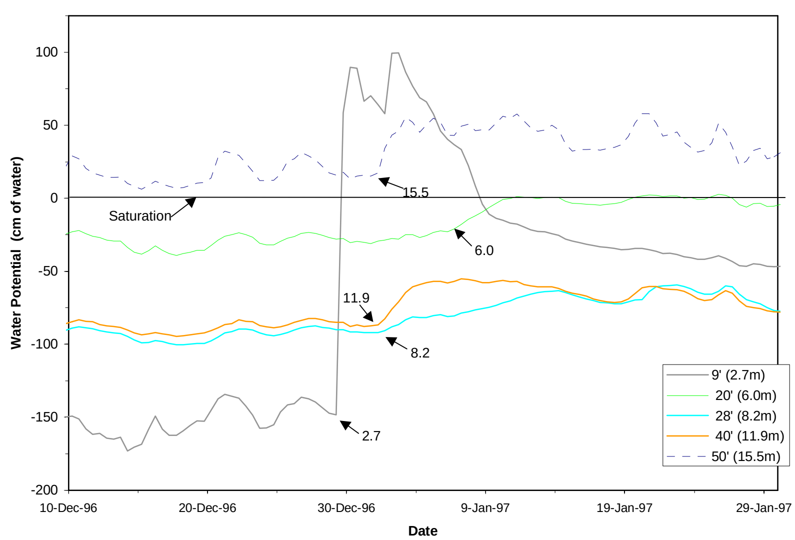

Figure D-5. Water movement through sediment-filled fractures in basalt into the 9.4-m interbed at the Radioactive Waste Management Complex. The flow rate of water through this interval is about 10 times lower than the example given above (Sisson and Hubbell 1999).

- Develop sensors to improve quantification of liquid, gas, and contaminant source term in the vadose zone. The majority of uncertainty in model predictions is based on the uncertainty of the source term flux at the contaminant source.

- Develop instrumentation installation techniques to produce representative measurements while ensuring that the installation does not bias the measurement.

- Develop methods for characterizing the hysteretic response of vadose zone instruments caused by fracture-matrix interaction. Finsterle and Faybishenko (1997) demonstrated through laboratory testing and numerical modeling that tensiometers in fractured rock respond during the wetting phase to fracture water potential and during the drying phase respond to the water potential of the rock matrix. This hysteretic response cannot be accounted for when correlating the measured tensions to the vadose zone conceptual model.

- Analysis of the potential biases of installing vadose zone monitoring instrumentation at locations where fractures intercept boreholes compounded by the effect of placing these instruments in a non-native porous media.

- Evaluate the accuracy of suction lysimeters when used to determine colloid concentration. If such a study indicates their accuracy is inadequate, new instrumentation should be developed to collect colloids in vadose zone materials.

- Develop in situ biological activity sensors to measure CO_2 flux (or some other direct or indirect indicator) in the deep vadose zone. Data from a biological activity sensor could be correlated to the location and the rate of contaminant degradation.

- The fracture basalt system will likely provide preferential flow pathways for contaminant transport. The ability at the INEEL to intersect and monitor each of these pathways is dubious using extant monitoring instrumentation. Lacking a direct method to monitor the vadose zone at each and every location, there is a need to statistically describe the transport of contaminants. In this light, there exists a need to develop indirect sensing instrumentation to measure state variables between the boreholes for spatial variability analyses.

- Design instrumentation packages to measure in situ relationships of transport processes. Examples of processes include moisture content, pressure head, hydraulic conductivity, and gas permeability. An in situ measurement eliminates sample handling and provides more applicable results.

- Develop methods for better quantification and calibration of existing probes to measure soil moisture content. Conversion of count rates, velocities, elapsed time, and other measurements to soil moisture content is problematic if conversion factors are developed on disturbed samples. In situ calibration over the full range of the measured values would improve the existing methods.

- Develop sensors for large-volume measurements of water potential and moisture content in porous media. Currently, water potential and moisture content are measure at a small scale (cubic centimeters to decimeters). Increasing the measurement scale to meet the numerical modeling need (e.g., cubic-meter size) would achieve representativeness.

D3.4 Characterization of Scale and Spatial Heterogeneity and Preferential Flow

D3.4.1 Summary

No accepted method exists for addressing the effects of spatial and temporal variations in fate and transport modeling. Inherent heterogeneity of soils, sediments, and rocks at widely different scales (ranging from molecular to the tens of kilometers) and non-uniform areal distribution of precipitation and infiltration cause deviations from ideal transport behavior in the vadose zone. Because of these heterogeneities, the properties that affect solute transport, the physical, chemical, and biological properties of materials, can be expected to vary spatially in the subsurface. The relative significance to water and solute transport of different scales of heterogeneity is unclear, but Wood and Norrell (1996) have reported that greater scales of observation result in more extreme variability of flow phenomena. Faybishenko et al. (1998) have proposed a hierarchy in which different flow models are used for different scales of investigation but find no evidence of scaling principles that would allow prediction of effects at one scale from observations at another.

Preferential flow, the process by which water and solutes move by preferred pathways, or fast paths, through a geologic medium (Helling and Gish 1991), presents one of the biggest dilemmas for monitoring in the vadose zone. Preferential flow in both fractured rock and soil is well documented and local wetting fronts may propagate to much greater depths than predicted, essentially bypassing the matrix pore space (Beven 1991). Figure D-6 shows evidence of preferential (finger flow) from a laboratory experiment of slow infiltration into a 1-m-diameter column packed with a very uniform quartz sand. Mechanisms for preferential flow in fractures include event-driven flow, film flow, and chaotic flow.

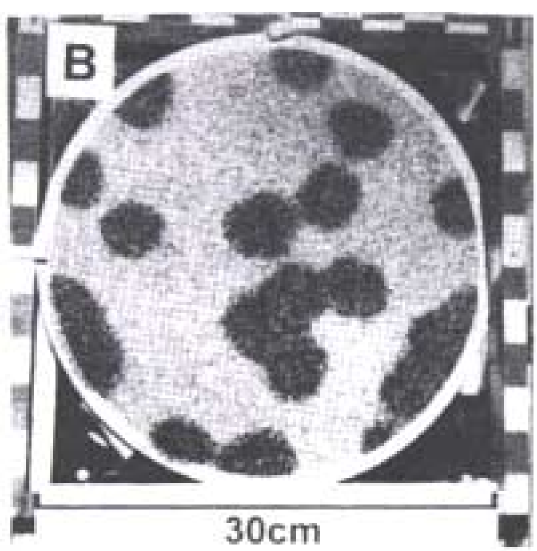

Figure D-6. Finger flow demonstrated in a small lysimeter at a high (8.6 cm/hour) infiltration rate in quartz sand. The dye pattern shows evidence of unstable flow (Yao and Hendrickx 1996).

Event driven flow occurs only sporadically under special circumstances such as flooding or increased infiltration because of major thunderstorms or unusually heavy snowmelt. Film flow, a process hypothesized to occur in fractures in porous media, occurs when a film of water of sufficient thickness to flow under the influence of gravity forms on the fracture walls. With thickness of at least 0.3 µm, films flow at rates of meters to tens of meters per day (Wan et al 1996). Because the relationship between moisture content and permeability of partially saturated rocks and soils is nonlinear (Pruess and Tsang 1990; Persoff and Pruess 1995), the flow processes in the vadose zone also are nonlinear. It is known from the theory of nonlinear dynamics (Abarbanel 1996; Tsonic 1992) that a combination of several nonlinear processes may lead to chaotic variations of the system parameters. In such systems, small changes in initial and boundary conditions may create new macroflow structures for different flow processes with no apparent scaling principles involved (Haken 1983).

Because the relative volume of rock or soil occupied by the fast paths can be very small, and yet carry most of the water and solutes, the data from randomly installed sampling units may be extremely variable and completely unrepresentative of the spatial average (Kung et al. 1991). Water and solutes easily can bypass instrumentation and samplers (Biggar and Nielsen 1976), leading to erroneous conclusions about the spatial extent of contamination. Such bypassing largely invalidates potential schemes to scale up, or combine responses in a meaningful way, from point measurements or borehole measurements, and challenges the capabilities of known geostatistical methods. Some geophysical methods such as seismic surveys and cross-hole tomography can provide integration over large volumes but lack the resolution to reveal fast pathways.

D3.4.2 Deficiencies

- No available instruments or methods can measure flow in single fractures or fluid movement at the fracture-matrix interface in sufficient detail to accurately represent transport
- Spatial averaging may provide nonrepresentative integration of point measurements
- No method is available for validating current assumptions of homogeneity and isotropy
- Classical approaches such as stochastic or deterministic methods for quantifying flow of water and solutes may not be valid if the stochastic component of the system is not the dominant factor.
- Alternative methods, such as chaotic analysis, have not been developed sufficiently for flow and transport in the vadose zone.
- Knowledge of INEEL spatial variability of sediment and volcanic facies in rock units is inadequate because of the degree of variability, making even drilling of boreholes an inadequate method for representing the heterogenous subsurface
- The relative significance of different scales of heterogeneity important for transport in the vadose zone is unknown
- No validated way exists to scale up laboratory-determined properties to field-scale conditions
- Spatial variability is a major factor limiting understanding of contaminant transport.

D3.4.3 Recommendations

To address the identified needs, INEEL scientists and managers should develop a field-scale vadose zone test bed or facility capable of both characterizing the heterogeneities in INEEL-area subsurface materials and assessing the effects of those heterogeneities on transport. The objectives of such a the test bed or facility should include the following:

- The development of instruments for site characterization and monitoring and for measuring properties and flux in fast paths
- Improved understanding of preferential flow mechanisms
- Identification of ways to determine the sample distribution required to represent a site
- The development, in a generic sense, of an understanding of how spatial variability affects transport
- Improved documentation and definition of existing heterogeneity and its impact on models
- The development of scale-up relationships for combining point measurements to represent a site
- The development of modeling approaches that account for individual flow paths
- Improved understanding of the facies distribution of sediments and basalts in the subsurface.
- Development of tracer tests that integrate small-scale effects into large-scale flow and transport.
- Design laboratory- and field-scale test together to identify correlations between laboratory- and field-scale results.

D3.5 Geochemistry

As water moves through the vadose zone, it carries dissolved chemicals. The chemicals do not necessarily migrate at the same rate as the water because of geochemical reactions between the solution, solid soil minerals, and the soil-gas phase. The interaction between dissolved contaminants in solution and solid phases in the vadose zone is most commonly described using a single, empirical distribution coefficient or K_d. Significant changes can occur in vadose zone solutions making explicit geochemical analysis important in fate and transport assessments. The use of a linear, reversible, constant adsorption coefficient does not explain the many processes controlling contaminant migration, particularly near the contaminant source. New approaches are required to explain the geochemical reactions.

D3.5.1 Summary

Geochemical reactions that control the fate and transport of contaminants through the vadose zone depend on the geochemical environment. The evolution and propagation of geochemical environments in the vadose zone depend on a complex interaction of hydrologic, biological, and geochemical processes:

- Plant root respiration and microbial degradation of organic matter raise the partial pressure of CO_2 in the vadose zone to 3 to 30 times greater than the concentration of CO_2 in the atmosphere. The proportional increase in CO_2 relative to depth is illustrated in Figure D-7.

  The two environmental factors that are most significant for directly affecting the rate of biological activity are the moisture content of the soil and the temperature of the soil.

- The dissolution of basic rock minerals by dilute carbonic acid controls the composition of natural waters. The pH of the water is determined by the balance between the dissolution of carbon dioxide from the gas phase and silicate and carbonate minerals from the rock matrix.

- Microbes in the vadose zone consume oxygen while converting soil organic matter to energy. In arid vadose zone environments, open pore space generally will be sufficient for diffusion of oxygen from the atmosphere to maintain oxidizing conditions in the vadose

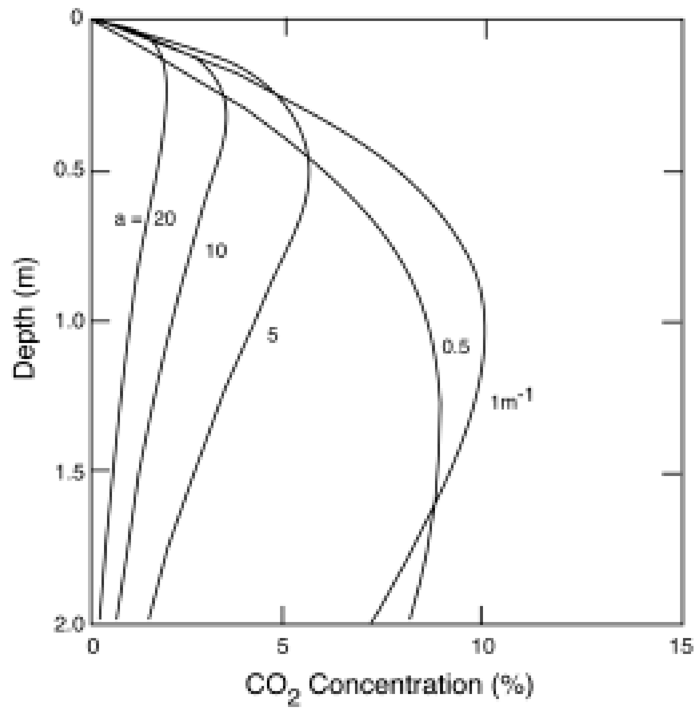

Figure D-7. Calculated soil profiles of carbon dioxide in the soil zone for different depth distributions of the carbon dioxide production function. Carbon dioxide levels in the soil are sensitive to the depth of maximum carbon dioxide production (Suarez and Simunek 1993).

zone. If the level of organic matter in the soil is high, or if pore space is filled with water, oxygen consumption may exceed replenishment through diffusion and reducing conditions may develop. If oxygen is depleted, microbes will use other inorganic compounds as electron receptors.

- Metals and radionuclides form soluble complexes with hydroxide, fluoride, phosphate, carbonate, and other ligands in solution. Waste may contain ligands such as ethylenediaminetetraacetic acid (EDTA), citrate, and oxalate from decontamination solutions. The extent to which complexes are formed can affect the ability of contaminants to adsorb from solution.

- Metals and radionuclides partition between the solution and mineral phases by adsorption reactions on the mineral surfaces. These adsorption reactions occur because of electrostatic effects (i.e., ion exchange) and because of specific chemical reactions (i.e., surface complexation). Surface adsorption reactions are the most important reactions for limiting the mobility of contaminants in the vadose zone.

- Plutonium has been determined in laboratory studies and field sampling programs to form colloids in water. Colloids are not reactive with exchange sites on rocks and minerals and have the potential to migrate at essentially the same rate as the water moving through the vadose zone.

- Acidic and basic waste solutions released to the vadose zone become neutralized through reaction with soil mineral phases.

- Solid phases in waste may dissolve over time, releasing contaminants to vadose zone solutions. Solid phases may precipitate from solution controlling solute concentrations by mineral solubility rather than by adsorption.

In general, performance assessment and risk assessment models typically do not address geochemical environmental factors, which can significantly impact transport.

D3.5.2 Deficiencies

One of the largest gaps in the application of geochemistry to fate and transport results from the use of linear, reversible sorption as the only mechanism governing the interaction between aqueous and solid phases during transport. Many waste management and remediation decisions are based on this very simplified conceptual model of the process by which metals and radionuclides in solution react with solid phases. Use of an empirical sorption coefficient precludes the incorporation of other geochemical processes in the evaluation of contaminant fate and transport. The deficiencies discussed below are associated with use of a linear, reversible sorption coefficient and the additional geochemical processes that are important in vadose zone fate and transport.

D3.5.2.1 Lack of INEEL Constants for Adsorption onto Solid Phases. While adsorption onto soil minerals is the most important control of the migration of contaminants through the vadose zone, conceptual models used to describe this process are empirical and do not address adsorption mechanisms. Thus, INEEL material-specific adsorption coefficients (i.e., mechanistic adsorption constants for transport) have not been established.

Limitations exist when using the distribution coefficient (i.e., K_d) for modeling contaminant transport (Triay et al. 1997). A constant, uniform, reversible, and generally low K_d has been used for most INEEL risk management decisions. Typically, K_d values for the vadose zone are not based on field-calibrated modeling or on measurements made on vadose zone geologic materials, but are values taken from literature or other sources. Sorption coefficients measured on ostensibly similar INEEL geologic materials (such as INEEL interbed sediments or INEEL basalt) give K_d values that vary by an order of magnitude or more (Colello et al. 1998; Liszewski et al. 1998). No correlation between substrate properties, solution chemistry, and the measured K_d values has been determined. As a result, no technical explanation for the variation is available. Therefore, the smallest available K_d values are used in predictive models to compensate for the lack of theoretical understanding.

Measurements of adsorption of metals onto soil materials show that adsorption is affected by pH and by formation of soluble complexes in solution. Figure D-8 shows the adsorption of zinc onto montmorillonite. At very low pH, adsorption by formation of surface complexes is inhibited by competition between hydrogen ion and zinc ion for adsorption sites. Some adsorption still occurs because of ion exchange sites on the clay. At a pH greater than 8, adsorption is decreased because zinc in solution in complexed by hydroxide and is not as available to adsorb to the clay. A constant K_d approach to adsorption would address neither the pH effects nor the formation of complexes in solution.

Surface complexation and ion exchange mechanistic conceptual models have been developed (Dzombak and Morel 1990; Kent et al. 1988; Davis and Kent 1990) with little transfer of the theory to fate and transport modeling. Geochemical codes frequently include ion exchange and surface complexation modules (Parkhurst 1995; Allison, Brown, and Novo-Gradac 1991; Serne, Arthur, and Krupka 1990; Appelo 1996). Reactive transport codes also include ion exchange and surface complexation processes (Lichtner 1996; Lieser 1995; Suarez and Simunek 1996, 1997; Yeh and Salvage 1997). Parameters to quantify the ion exchange and surface complexation processes have been

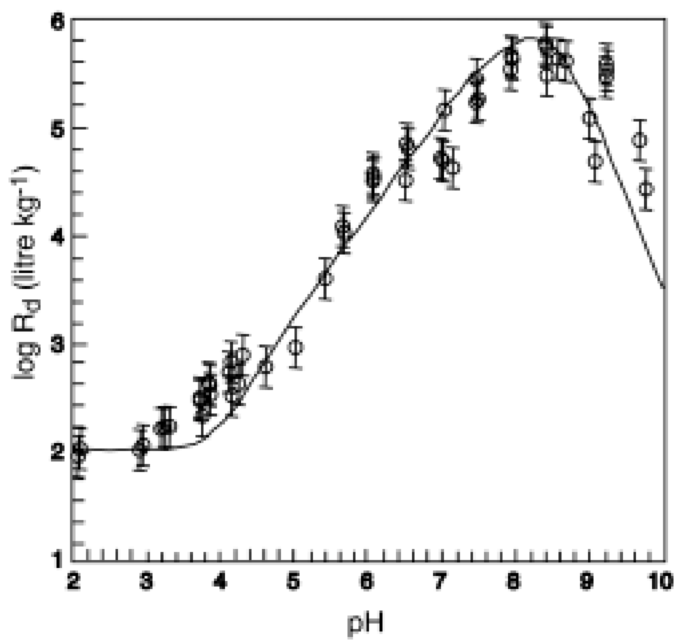

Figure D-8. Adsorption of zinc onto sodium-montmorillonite as a function of pH. The adsorption coefficient (R_d) is calculated the same way as the distribution coefficient (K_d), but is not assumed to be constant at all pH values (Bradbury and Baeyens 1997).

measured in laboratory settings for pure mineral phases. Almost no work has been done to develop these parameters for soils. Surface complexation and ion exchange mechanisms have not been used in performance assessment or risk assessment fate and transport codes.

D3.5.2.2 Unknown Presence of Complexing Agents. The presence of complexing agents in waste and wastewater at the INEEL has not been evaluated. The formation of aqueous complexes in soil solutions can sequester contaminants in solution and inhibit solution-solid reactions that retard the migration of contaminants.

Decontamination solutions containing complexing agents such as citrate, oxalate, and EDTA were used and disposed of by injection wells, released through spills, and buried in waste. Inorganic anions such as fluoride, carbonate, and phosphate can form aqueous complexes with contaminants. No measurements of organic complexing agents have been made on INEEL soil or groundwater. Anions are not always measured because they are not considered contaminants.

D3.5.2.3 Conditions Leading to Facilitated Transport Not Understood. Facilitated transport of actinides in colloidal form has not been evaluated at INEEL disposal sites. Migration of plutonium to sedimentary interbeds underlying buried waste at the Subsurface Disposal Area has apparently occurred at a rate much faster than could be predicted by solute transport processes. Americium also may be migrating much faster than reactive transport models with adsorption would predict.

Plutonium has been determined in laboratory studies and field sampling programs to form colloids in water. Current studies at Clemson University with actinides and INEEL basalts indicate that facilitated transport of some kind is possible. Colloids are not reactive with exchange sites on rocks and minerals and have the potential to migrate at essentially the same rate as the water moving through the vadose zone. The geochemical conditions that would contribute to the development of colloids have not been demonstrated. No combination of K_d values has been shown to appropriately represent facilitated transport with a K_d model. Facilitated transport can be much more event driven (i.e., with a short duration and a large water flux) than transport of dissolved-phase contaminants. Computer codes currently used by the INEEL cannot simulate facilitated transport. Projects at the INEEL have addressed contaminant transport through analysis of contaminants in the liquid phase. The geochemical conditions that would contribute to the development of colloids have not been demonstrated.

D3.5.2.4 Unknown Effects of Redox Potential. The effect of the redox state on actinide transport at the INEEL is not understood. Mineral solubility and the adsorption onto surfaces of minerals are highly dependent on the redox state of metals and radionuclides that can occur in multiple oxidation states.

The geochemistry of actinide radionuclides, particularly plutonium, is remarkable in its complexity. Actinides can be present in the vadose zone in several oxidation states. The mobility of actinides is highly dependent on the oxidation state. The vadose zone at the INEEL likely is oxidizing because oxygen can diffuse through the open pores to maintain oxidizing conditions. However, in buried waste with organic carbon present at high concentrations, reducing conditions may develop. Redox processes in waste that transform buried waste and mobilize contaminants are not understood.

D3.5.2.5 Unknown Rates of Leaching and Release from Sources. Leach rates and release mechanism from contaminated sediments and buried waste at the INEEL have not been established. The release of contaminants from buried waste and contaminated sediments is a key element in the migration of contaminants to groundwater.

The geochemical conditions in buried waste are very complex with variable redox environments, microbial activity, corrosion of waste containers, dissolution of solid phases, and desorption of contaminants from sediments. The reversibility of reactions, kinetics of reactions, and the impact of microbial activity are all important factors on the rate of contaminant release.

D3.5.2.6 Unevaluated Reaction Rates. The rates of interphase mass transfer reactions relative to the rate of water movement have not been evaluated at the INEEL. All adsorption reactions have been considered to be in equilibrium.

Geochemical reactions occur in time periods from milliseconds to centuries. The time required for most intrasolution reactions to occur is short enough that equilibrium can be assumed. However, for mass transfer reactions between phases, and for microbiologically mediated reactions, reaction rates can be slow relative to the rate of water movement. For these reactions, equilibrium is not a good assumption and the rates at which reactions occur must be explicitly evaluated.

D3.5.3 Recommendations

Laboratory studies can measure parameters and develop theories of important reactions. Computer models can show the relative importance of processes. However, sampling and analysis of field sites are needed to provide information on the geochemical environment in the vadose zone and verification of the processes occurring in the field. Specific recommendations to enhance understanding of geochemical issues are provided below.

- Implement the surface complexation and ion exchange models as mass transfer reactions in fate and transport models and use them to replace the empirical K_d approach. A database of exchange constants for minerals and soils will need to be developed, and the relative selectivity of surfaces for metals and radionuclides should be determined. The models will still be empirical at this time because the selectivity coefficients and types of surfaces are not well known. These types of models are important to advance the level of modeling of pollutants and radionuclides in the environment and the effect of the geochemical environment on contaminant transport.

- Conduct a study of the processes and mechanisms controlling the propagation of pH in the vadose zone and how to incorporate these processes into a predictive reactive transport code. Most geochemical codes can speciate metals or radionuclides given the pH, but cannot generate these environmental factors from mechanisms such as biological activity. The ability to calculate the gas-phase carbon dioxide concentrations mechanistically is important to developing a predictive biogeochemical model of the vadose zone.

- Determine the geochemical conditions that lead to the formation of actinide colloids. The mechanisms for transport of colloids need to be better defined and related to the flow conditions present in the subsurface.

- Evaluate the reaction kinetics and transport rates to select problems and situations in which reaction rates are important to understanding migration. Most vadose zone geochemical reactions important for contaminant transport appear to be relatively fast. Kinetics of adsorption reactions is generally complete in a matter of hours to a few days. This reaction rate is generally faster than the rate of water movement in the vadose zone permitting equilibrium in geochemical reactions to be approached. In the spring, rapid recharge of snowmelt can result in very fast movement of water through coarse-grained materials. Kinetic factors may play an important role in contaminant migration.

- Measure the potential complexing agents in soil and groundwater to evaluate the presence and identity of these agents. Thermodynamic data to calculate the ability of the complexing agents to sequester contaminants in solution are available for many complexing agents and contaminants. Laboratory work may be needed to develop thermodynamic data for other compounds. The persistence of these complexing agents in the vadose zone then needs to be evaluated to determine their persistence for contributing to transport.

- Evaluate the biogeochemical reactions in buried waste to assess the development of reducing conditions in waste and the use of other electron receptors than oxygen by microbes. The fate of contaminants in buried waste are closely linked to the redox environment and the redox state of the contaminants. This information can be used to develop release rates from buried waste.

D3.6 Characterization of the Geologic Framework and Hydrologic Properties

D3.6.1 Summary

All vadose zone transport processes occur within the geologic framework. The geometry and the physical and chemical properties of the framework largely control the rate and manner in which water and solutes move in the subsurface. Knowledge of the geologic framework at the INEEL is derived mostly from drilling, logging, and sampling of materials in wells and exploration boreholes. In addition, a limited number of areas in which erosion or uplift have exposed vertical cross sections of the subsurface materials (see, for example, the Box Canyon site description in Appendix A) provide insight into the distribution of rocks and sediments between wells and boreholes.

The vadose zone at the INEEL comprises basalt lava flows and interlayered sediments (see Appendix C). Emplacement and deposition mechanisms for these materials are generally known (Hackett and Smith, 1992; Kuntz, Covington, and Schorr 1992) but not to the level of detail necessary for realistic modeling of subsurface transport. For example, basalt lava flows are known to have very irregular upper and lower contacts, fractured zones near the contacts, massive interiors, and blunt terminations, but site-specific geometries for these features are inferred from observations at only a few points in drill holes. Likewise, sediments are known to have varied origins (alluvial, eolian, and lacustrine deposits), exhibit abrupt and significant changes in thickness, occur more frequently in some areas than in others, possess facies gradations, and range in texture from fine-grained, impermeable layers to very coarse permeable gravels. However, applying this knowledge to site-specific subsurface geometry based on only a few drill holes is sketchy at best and contributes to significant uncertainty in interpretations and model results.

Because of the heterogeneous nature of the lithologic units, hydrologic properties exhibit extreme spatial variability and unpredictability. Some properties have been measured for small samples in the laboratory but, because of the heterogeneity of the system, it is not possible to scale up or combine those measurements in any meaningful way to large volumes. In situ measurements of infiltration rates and aquifer behavior have been done at some places, but do not provide site-specific information for problem sites. Inherent difficulties in measuring the in-situ physical and hydrologic properties arise from the non-uniform distribution of fractures in the basalts, the unconsolidated to poorly lithified nature of the sediments, and the unavailability of instruments or methods to measure important vadose zone properties. Figure D-9 shows a geologically permissible geometry for the distribution of basalts and sediments in the vadose zone at the INEEL. Because of the small number of wells and boreholes, many other geometries are possible.

D3.6.2 Deficiencies

Deficiencies in knowledge of the geologic framework arise from both geometric and rock property uncertainties. Both contribute to limitations in the understanding of vadose zone transport processes, and both are, in part, related to the heterogeneous nature of the geologic materials (see Section 3.1).

D3.6.2.1 Geometric Uncertainties—Deficiencies in knowledge of the geologic framework arising from geometric uncertainties include the following:

- The inability to effectively assess the site-specific, three-dimensional distribution of basalts and sediments in the subsurface
- Unrealistic model results based on simplifying assumptions that the layering is uniform and that sediment interbeds can be treated as a single layer
- Inadequate knowledge of interrelationship and interconnectivity of various fracture sets in basalt lavas
- Inadequate knowledge of the detailed geometry of fracture surfaces
- Inadequate site-specific knowledge of the distribution of different facies of the basalts and sediments.

D3.6.2.2 Rock Property Uncertainties—Deficiencies in knowledge of the geologic framework arising from uncertainties in the physical and chemical properties of rocks include the following***:***

- A paucity of data. Only a few laboratory measurements of hydrologic properties in small samples and almost no in situ, bulk hydrologic property measurements have been made.
- A lack of scaling relationships for relating laboratory data to bulk property data. At best, the scaling relationship will be empirical requiring much site-specific work, which has not been done. At worst, no scaling relationships exist.
- A lack of instruments or methods for measurement of in situ properties of large volumes of material. Measurement of in situ properties in large volumes of material is inherently difficult.
- Insufficient bulk in situ data. The inherent characteristics of the geologic framework present difficulties for obtaining such data. The unconsolidated sediments cave into boreholes, producing cavernous openings and contributing to difficulties in measuring sediment properties with borehole geophysical methods. The fractured, vesicular, brecciated basalts commonly have infillings of sediment, which change its hydrologic properties dramatically.
- Rudimentary knowledge of the chemical and mineralogic makeup and sorptive properties of sediments and basalts. While many analytical and laboratory studies are required to advance the level of understanding adequately, only a few have been completed.

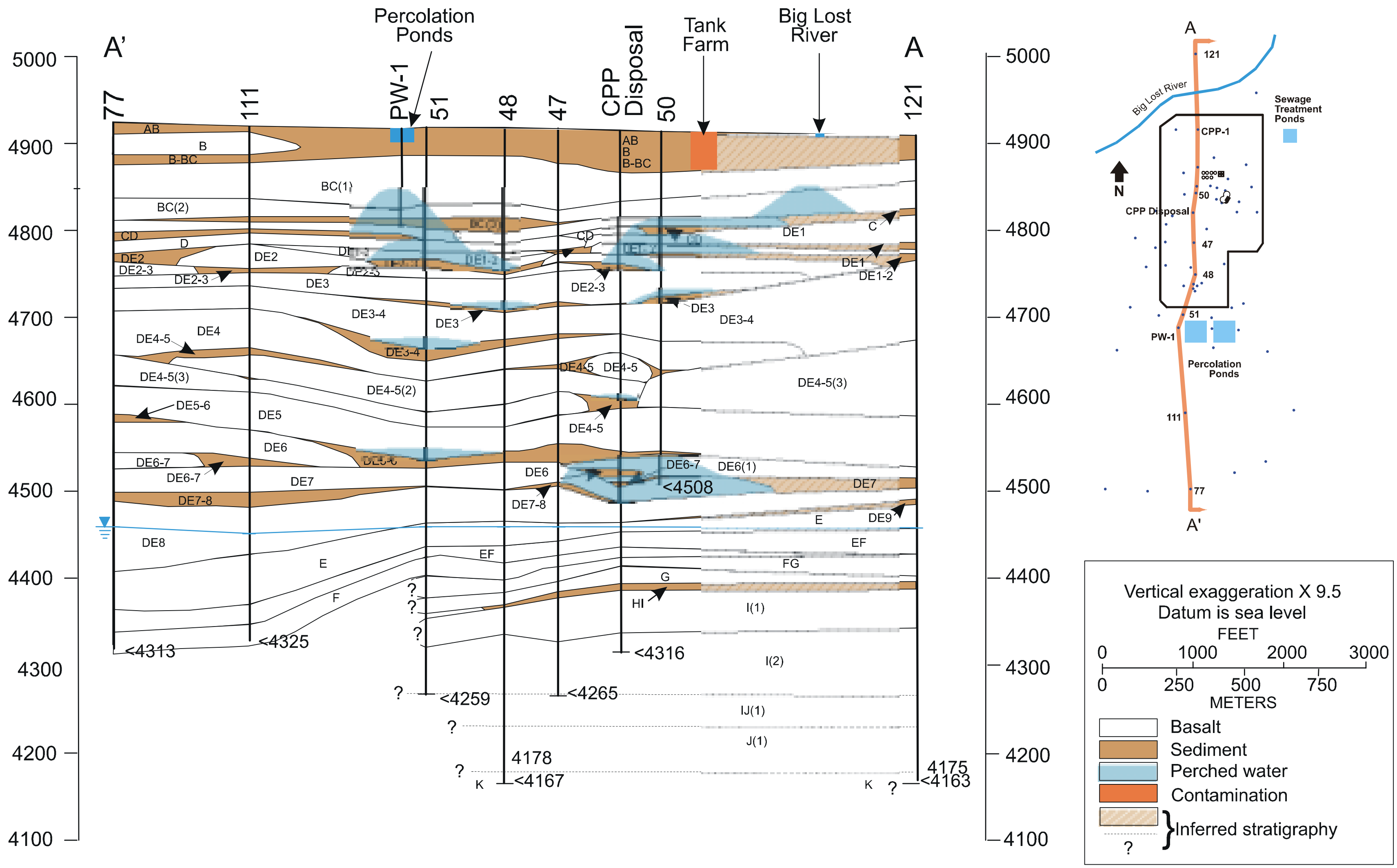

Figure D-9. Cross section of the vadose zone at the Idaho Nuclear Technology and Engineering Center. Note the swelling and pinchouts of sedimentary layers, the blunt terminations of basalt lava flows, and the significant deviations from "layer-cake" stratigraphy.

D3.6.3 Recommendations

A field-scale vadose zone test bed or facility is required to address the deficiencies in knowledge of the geologic framework. The objectives of such a test bed or facility should include the following:

- The development of vadose zone models that use realistic stratigraphic interpretations developed from best current knowledge for all facility areas and for the INEEL as a whole

- Improved geophysical methods for imaging subsurface geometry (both surface and borehole methods, including cross-hole tomography)

- The development of tools and methods for measuring or estimating bulk, in situ hydrologic properties important for vadose zone processes

- The development of tools and methods for collecting large, undisturbed samples (approximately 1 m^3 in size) of sediments and basalts for physical property tests and measurements in a laboratory environment

- The development of a laboratory or test facility capable of handling and testing large, undisturbed samples

- The development of better geostatistical methods to interpolate lithologic information between boreholes

- Additional chemical and mineralogic analyses and sorptive studies of sediments and basalts.

D3.7 Geophysical Methods

D3.7.1 Summary

Geophysical methods measure the physical, chemical, and electrical properties of materials to reveal their subsurface distribution. It is important to use the right combination of geophysical methods to obtain the required information. Geophysical techniques available for characterization of the vadose zone are discussed below. Many of them have been used with varying degrees of success at the INEEL.

Ground-Penetrating Radar—Ground-penetrating radar (GPR) techniques rely on the use reflected radar beams to image contrasts in radar wave transmission within the subsurface.

Electrical—Electrical geophysical techniques rely on electrical current injected into the ground to image electrical properties of the subsurface. The following electrical techniques have been employed previously for vadose zone applications:

- Resistivity

- Time-domain reflectrometry (TDR)

- Induced polarization (IP).

Electromagnetic Fields—Electromagnetic field (EM) geophysical techniques involve the induction of current flow in conductors and then the detection of the secondary field from the induced current flow within the conductors. The following EM methods have been employed previously for vadose zone applications:

- Frequency-domain electromagnetic field (FDEM)
- Time-domain electromagnetic field (TDEM)
- Very low frequency (VLF)
- Controlled source audio-frequency magnetotellurics (CSAMT).

Potential Fields—Potential field geophysical techniques exploit distortions in the earth's magnetic, gravitational, and electrical fields to detect objects and rock masses of contrasting properties. The following potential-field techniques have been employed previously for vadose zone applications:

- Magnetism
- Self potential (SP)
- Gravity.

Seismic—Geophysical seismic methods exploit contrasting seismic velocities in the subsurface to detect objects of interest and rock masses of contrasting properties. The following seismic techniques have been employed previously for vadose zone applications:

- Reflection
- Refraction.

Radiometric—Radiometric geophysical techniques rely on natural radiation for inference of the content of radioactive elements and isotopes in rocks and contaminants.

Borehole—Borehole techniques rely on the insertion of a variety of tools (or sensors) in a borehole to detect and measure differences in rock or soil properties. The following borehole techniques have been employed previously for vadose zone applications:

- Gamma (rock composition)
- Gamma-gamma (density)
- Neutron (water content)
- Sonic (seismic velocity)
- Caliper (rock strength)
- Acoustic borehole televiewer (i.e., fractures and in situ stress)
- Borehole video (i.e., fractures and rock texture).

Cross-Borehole Tomography—The tomographic geophysical methods work the same way as their surface counterparts. The surveys are arranged in adjacent boreholes to provide three-dimensonal information within the survey area. The following cross-borehole tomographic techniques have been employed previously for vadose zone applications:

- Radar
- Seismic
- Acoustic
- Electric.

In Table D-2, a list is provided of the most common geophysical methods used at the INEEL along with their capabilities to determine physical, chemical, and electrical properties.

D3.7.2 Deficiencies

All geophysical methods have limitations that to varying extents affect interpretation and the resulting data. Therefore, it is important to use several methods together to minimize the limitations. The overall deficiencies of geophysical methods used at the INEEL include the following:

- Insufficient data are available to determine optimal survey locations and parameters
- Several surveys that have been done do not have the data sets archived for future use or for reprocessing
- Geologic and cultural noise, for example, human-created metallics such as a power line, limit the effectiveness of geophysical techniques and have affected the usefulness of some of the surveys performed at the INEEL. Geological and cultural noise affects all geophysical techniques to varying degrees, which requires the use of a suite of techniques to compensate for the noise problems and to evaluate different aspects of the same objects to yield the maximum amount of information.
- High-velocity basalt overlying lower-velocity interbeds limit the use of seismic reflection and refraction techniques
- High conductivity of the soil at the INEEL limits the usefulness of radar methods
- Electrical properties of most chemical contaminants do not have large enough contrasts from the background to delineate by active geophysical methods.

D3.7.3 Recommendations

Deficiencies in geophysical techniques include both research and development to improve survey designs to make maximum use of existing methods over conventional as well as new types of targets. The following activities are recommended to address those deficiencies:

- Test several geophysical methods to determine the optimal survey parameters along with the optimal combinations of techniques

Table D-2. Common geophysical methods used at the INEEL and their capabilities to determine physical, chemical, and electrical properties.

	Type of Geophysical Method							
Application	GPR	Resistivity	SP	IP	EM	Potential Fields	Seismic	Tomography
Geology		√			√	√	√	√
Fractures	√	√		√	√	√	√	√
Moisture	√	√		√	√			√
Fluid migration	√	√	√	√	√			√
Temperature change		√						√
Ion concentration change	√	√		√				√
Depth of penetration	Low	Variable		Variable	Variable	Variable	Variable	Variable
Chemical contamination		?	?	?	?			
Saturation (water table)	√	√		√	√		√	√
Noise susceptibility	High	Low		Low	High	High	Low	Low
Reconnaissance					√	√	√	
High resolution	√	√	√	√	√	√	√	√

Acronyms

GPR	Ground-penetrating radar
SP	Self potential
IP	Induced polarization
EM	Electromagnetic

- Conduct field tests to screen geophysical techniques for specific problems at INEEL sites
- Perform long-term monitoring using geophysical methods at several sites to determine seasonal changes
- Develop a geophysical database and a location to archive data for future use
- Perform additional work on a geophysical methods to locate and delineate in situ chemical plumes
- Increase spatial resolution of tomography techniques
- Acquisition of hardware and software to perform surveys.

D3.8 Microbiology

D3.8.1 Summary

Microorganisms exert a profound influence on the environment. For vadose zone study, two significant microbial activities are microbially influenced corrosion and biological modification of contaminant fate and transport. With the exception of the well-studied organic topsoil layer, the literature contains very little data on vadose zone microbiology. Reports on vadose zone microbiology indicate that relatively low levels of biomass are present and that the distribution of the biomass is generally unpredictable (Hersman 1997). The chief limiting factor on microbial activities appears to be water availability, though the effects are often indirect. For example, nutrient transport is a limiting factor rather than dessication (Frederickson et al. 1993; Holden and Firestone 1997; Kieft et al. 1993). It is likely that temporal variations in water availability, which are largely unstudied, may significantly alter the activities of microorganisms in the vadose zone (Brockman et al. 1992; Colwell 1989; Frederickson et al. 1993).

Similar to other sites worldwide, scant data on the microbiology of the vadose zone at the INEEL have been produced. Verifying that microbes from a core sample actually originated from the subsurface and are not from the surface (e.g., drilling fluids) is a critical part of subsurface microbiology (Colwell et al. 1992) at the INEEL and elsewhere. Therefore, sampling methods are discussed below. Colwell (1989) reported on the microbiology of three cores from the 240-ft sedimentary interbed (i.e., also referred to as the C-D interbed) at 70 m below ground surface (bgs) in the vadose zone near the RWMC. Cores samples were taken by air-rotary coring with prefiltered air, and aseptic core processing methods were employed to reduce the likelihood of sample contamination. Total cell counts for these deep, vadose zone sediments were about 3E+05 cells per dry gram, which was one order of magnitude less than comparable surface soils (3E+06 cells/dry g) taken at this site. No culturable organisms were found in one core while the other two cores had 50 and 21 colony-forming units (CFU)/dry g, respectively, compared to 3.5E+05 CFU/dry g for surface soil at this site. The significance of this study was the documentation of the existence of viable microorganisms at depth in vadose sediments from an arid region. The percent of culturable organisms (CFU/total cell counts * 100) was very low (< 0.05%) in the vadose sediments compared to the surface soils (approximately 10%). This low percent culturability could be caused by (1) inadequacy of culture techniques in growing potentially viable organisms or (2) dead-cell biomass (i.e., the majority of the organisms were dead). Dead cells are usually rapidly metabolized in the environment; however, the generally unfavorable conditions at this location could have suppressed the rapid turnover of dead cell biomass. Colwell (1989) speculated that intermittent recharge events could provide nutrients and waters to sustain organisms in these sediments and provide a mechanism of cell transport for colonization.

Kieft et al. (1993) reported on the microbiology of cores taken in 1990 from Coreholes W01 and W02 at the site of the proposed New Production Reactor (NPR) east of the INTEC. These cores were collected by reverse-air circulation rotary coring using argon and were aseptically processed on site (Colwell et al. 1992). Data from multiple tracers of potential sample contamination indicated very high quality samples were recovered. In fact, no aerobic heterotrophic organisms were cultured from 10 cores taken from between 69.6 m and 139.9 m bgs. Despite the absence of culturable heterotrophs, an average of 1E+07 cells/dry g was reported for these cores. Activity measurements using ^{14}C-labeled substrates showed extremely low levels of mineralization, many below detection levels and all below 10% mineralization of the added labeled carbon. The values for culturable heterotrophs and activity were significantly less than values observed in vadose zone cores from sites at Hanford and the Nevada Test Site (Kieft et al. 1993). The significance of Kieft's study is the report of microbiology data from deep crystalline rock in the vadose zone and the near absence of activities detected in the laboratory with the methods that were used. Palumbo et al. (1994) examined these same samples for the potential for stimulation of by nutrients and water. A minority of the core samples responded positively to addition of water while a slight majority responded positively to water plus nutrients. Palumbo et al. (1994) speculated that the low amount of carbon in these samples and the flux of that carbon in situ could limit microbial activities.

Rogers (1998) reported on the microbiology of a depth profile for cores taken from three coreholes in the eolian sediments overlying the basalt flows at the RWMC. Coring was done by hollow-stem auger, and an aseptic technique was used to collect subsamples from cores taken from less than 1 m to about. 7 m bgs. The context for this effort was investigations into microbially influenced corrosion of buried waste containers. Heterotrophs and acid producers were commonly recovered from these samples while *T. thiooxidans* was not found, and only an occasional positive was observed for dissimilatory nitrate-reducing bacteria (DNRB) and sulfate-reducing bacteria (SRB). The data from the three coreholes suggest a small spike in numbers of heterotrophs at around the 2-m depth and then very low values down to about 6 or 7 m where the number of culturable heterotrophs noticeably increases. Work by Rogers also was reported in Mizia et al. (1999) in which the presence of microorganisms of different physiologies was assessed in soil samples and on metal coupons buried at 1.5-m and 3-m depths at the RWMC. Liquid and solid media enrichments showed that heterotrophic bacteria, acid formers, actinomycetes, and fungi were found in all soils and on all types of metal coupons. No DNRB or *T. thiooxidans* were recovered from soil or the coupons while SRB were only found in the soil. The absence of DNRB and the presence of high levels of oxygen found by soil gas analysis indicated the predominance of an oxic environment. In situ microbial activity was inferred by decreasing O_2 and increasing CO_2 with depth in the soil profile.

D3.8.2 Deficiencies

D3.8.2.1 Lack of Data. The primary deficiency in understanding vadose zone microbiology is the impressive dearth of data, especially at the INEEL. The data are so sparse that drawing meaningful conclusions is difficult about basic issues such as which metabolisms are present, how the organisms are distributed, and which physical and chemical factors control their distribution. Data from Rogers (1998) suggest some interesting trends in the microbiology of the upper 10 m of the vadose zone at the RWMC. These data indicate an anomalous peak in culturable organisms at about the 2-m depth and another at about 6 m—probably the interface of the surface sediments with the upper-most basalt flow.

D3.8.2.2 Inaccessibility of In Situ Analytical Sites. The specific deficiencies in conducting a microbiological study of the vadose zone relate to the inaccessibility of the study location and the inability to remotely detect microbial activity. These constraints force the requirement of costly sampling methods. The low levels of biomass in the vadose zone increase the effort necessary to discriminate a low signal (i.e., autochthonous biomass) against a much larger background of potential contaminant organisms (i.e., allochthonous biomass) (Colwell et al. 1992).

D3.8.2.3 Inability to Estimate In Situ Activity. The inability to accurately estimate in situ activity, especially in the vadose zone environment in which many organisms are unculturable, remains a principle obstacle in understanding vadose zone biotransformations.

D3.8.3 Recommendations

Focusing vadose zone microbiological activities on two overarching areas of study is clearly recommended to advance the level of knowledge of vadose zone microbiology at the INEEL:

- Development of an understanding of the basic distribution of microbial physiologies and the abiotic factors that control their distribution

- Development of an effective and efficient method for determining rates of in situ biologic activity.

Specific recommended activities to implement the two areas of study include the following:

- Thoroughly characterize the vadose zone microbiology of a research site (vertically and horizontally) so that sufficient data are produced to achieve the development of a conceptual model of microbial processes in the vadose zone at a particular site. Given the low-percent culturability of microbes observed in deep vadose core samples from the INEEL, emphasis on culture-independent techniques is particularly warranted to explore basic and applied implications of high numbers of cells that cannot be cultured. In a ranking of environments in terms of microbial activity, deep arid vadose zones rank near the lowest of those investigated (Onstott et al. 1999) and require special attention to method detection limits.

- Conduct temporal studies incorporating alterations in water availability (natural or manipulated) to allow a full appreciation of the range in activities that may be exhibited. This characterization might be tuned to specific issues of concern, for example, microbial corrosion of buried waste containers or contaminant fate and transport.

- Develop accurate measurement methods for in situ microbial processes. Accurate measurement of microbial processes has proved to be nearly unattainable in all settings including the vadose zone. In the saturated zone, geochemical analyses of groundwater can assist in bounding rates of biological transformation. In the vadose zone, gases or mineralogical alteration could be examined. The work of Wood, Keller, and Johnstone (1993) offers a model for CO_2 measurement in the shallow vadose zone that could be adaptable to greater depths. Innovative approaches for assessment of in situ microbial activities are required for the vadose zone and other microbial habitats.

D3.9 Surface Covers

D3.9.1 Summary

Isolation and containment through the use of engineered surface covers is an often-used method for dealing with waste in the vadose zone. At the INEEL, engineered surface covers have been used to remediate waste sites at several facilities (e.g., the CFA landfills, the Stationary Low-Power Reactor No. 1 [SL-1] burial ground, and the Boiling Water Reactor Experiment I [BORAX-I] burial ground). It is not unlikely that surface covers will be chosen as the method of remediation at other INEEL waste sites. Because surface covers will be expected to function over extended time frames (of hundreds of years or longer), it is imperative that their designers and users understand their long-term behavior. Regulatory agency and public acceptance of waste isolation and containment in the vadose zone will depend largely on evaluations of the long-term performance of the covers.

D3.9.2 Deficiencies

D3.9.2.1 Incomplete Understanding of Cover Performance. The movement of water through buried waste generally is the major mechanism for transporting the waste beyond its original boundaries. Therefore, limiting net infiltration into the waste is of primary concern. Current practice in the design of surface covers to limit net infiltration generally follows the design guidance developed by the EPA. The standard EPA cover comprises a surface layer to foster vegetative growth, a drainage layer, and a low-permeability composite layer consisting of a geomembrane placed directly over compacted soil. This design may be prohibitively expensive for large waste sites (including the RWMC Subsurface Disposal Area) and alternatives are being sought, particularly in arid regions with low annual rainfall.

The CFA landfill covers are examples of alternative covers that rely on a compacted soil layer to restrict downward water movement but omit the geomembrane and drainage layers. Such a design is typical of covers constructed during the past few decades. However, increasing evidence suggests that covers that rely on compacted soil layers to restrict water movement are likely to fail in the long term. Indeed, post-closure monitoring of the CFA landfill covers already indicates that water is moving through the compacted soil layer even though preliminary modeling of the covers predicted that water movement through the compacted soil layer would be below detectable limits. The unexpected results undoubtedly arise from a combination of factors including, but not limited to, incomplete understanding of the cover's performance and the inability of the predictive model to accurately describe the relevant cover processes involved.

It is evident that there is a lack of understanding of how traditional soil cover designs (that have been used for decades) function, particularly over the long term. Surface cover performance is typically assessed using a combination of material tests, field tests, and numerical simulations. However, these activities often fail to account for possible future changes in material properties and in environmental processes that affect the covers. In addition, alternatives to the standard EPA cover (such as water storage-evapotranspiration type covers), rather than depending on a specific material property, rely on several natural, interactive processes to function effectively. This makes performance assessment, particularly for the long term, even more challenging.

Because of a lack of understanding of surface covers, the INEEL has undertaken several surface cover research projects. The Engineered Barrier Test located at the Engineered Barrier Test Facility is being used to quantify hydrologic properties of alternative soil covers and evaluate drainage under a range of surface conditions (see Figure D-10).

The Protective Cap/Biobarrier Experiment is being used to evaluate ecological and hydrologic properties of the standard EPA and alternative covers. The Simulated Waste Burial Trench Caps project (in existence for nearly 10 years) has been used to measure runoff and erosion from natural and induced snow-melt events and accelerated rainfall (irrigation) on sloping surfaces. Taken together, these projects provide a wealth of information. However, the needs related to understanding cover behavior and predicting long-term performance extend beyond current testing.

D3.4.1.1 Lack of Quantification of Data. Remediation objectives vary from site to site so, in addition to limiting net infiltration, cover designers also must consider other factors such as plant, animal, and human intrusion control, vapor and gas control, wind and water erosion control, and providing isolation from radiation. The rock rip-rap surface covers employed in the remediation of the SL-1 and BORAX-I sites were designed primarily to provide a shield from penetrating radiation, inhibit biotic

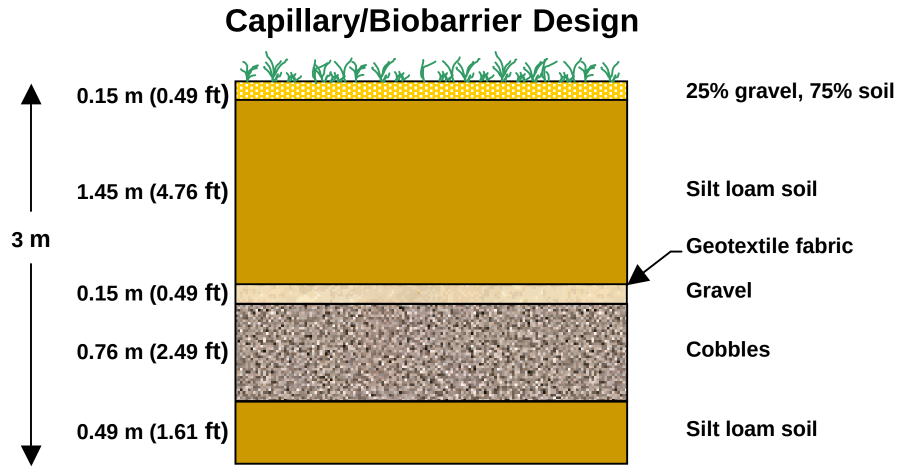

Figure D-10. Example of an alternative surface cover being tested at the INEEL.

intrusion by deep-rooting plants and burrowing animals and insects, and discourage human intrusion. The risks from migration of contaminants to the underlying aquifer were determined to be minimal, so limiting net infiltration was of little concern in the design of the cover. However, rip-rap covers are likely to increase infiltration and minimize evaporation. No data exists quantifying these processes and the subsequent effect on contaminant migration. Over the long term, deep-rooted plants also may colonize these covers resulting in contaminant uptake and transport to the surrounding environment. Again, this type of process is currently not quantified.

D3.9.2 Recommendations

Further research is needed to complete the following activities:

- Collect data on the hydrologic performance of covers. Few data exist for traditional covers with resistive barriers, and even fewer data exist for alternative covers.
- Collect data on field performance of traditional and alternative cover materials.
- Assess the service life of covers and cover components.
- Determine the amount of differential settlement surface covers can withstand before their ability to meet design objectives is compromised. Settling of underlying waste is a problem at numerous burial sites including the SDA at the INEEL.
- Determine the effects of seismic motions on the integrity and performance of surface covers.
- Develop standard procedures for evaluating the shear strength at interfaces between cover materials. This is an important factor affecting the stability of covers on slopes and can also be affected by moisture conditions, freeze-thaw cycles, heating-cooling cycles, and creep.
- Develop alternative cover designs, particularly those using natural materials and processes that may survive in the long term better than manufactured materials.

- Develop technical guidelines for demonstrating alternative cover equivalency to mandated designs.
- Develop monitoring guidelines that will ensure the covers are functioning as intended.
- Evaluate computer models used for simulating the near and long-term hydrologic performance of covers. Adequate verification of model results with field data covering a range of cover designs, materials, and environmental conditions is lacking.

D3.10 Physics of Flow

D3.10.1 Summary

Conservation of momentum, energy, and mass is used to define the state of a real-fluid system quantitatively (Probstein 1989). When applying conservation laws, the fluid is assumed to be a continuum and constitutive relationships (e.g., Newton's law, Fick's law, and Fourier's law) are required to describe the physics of flow in a system.

The vadose zone is a difficult environment within which to predict water movement because its complex geologic structure is compounded by the wide variety of scales at which flow can occur. The traditional approach to describe and predict the migration of water in the vadose zone is based on Richards' equation (1931). This equation has been verified in both laboratory and field experiments in a number of different time and space scales in porous media. However, Richards' equation can be misapplied such as when preferential flow is a significant water transport phenomenon in, for example, fractured porous media. Richards' equation often is implemented using large-scale volume averaging to describe the flow system at the site scale. This type of averaging has the advantage of producing a numerical solution within a reasonable amount of time. However, it has not been established whether large-scale volume averaging can represent the physics of variably saturated flow properly in systems with fast preferential flow components (Pruess, Faybishenko, and Bovarsson 1998).

Examination of field sites and laboratory sandbox experiments has shown that complex wetting-front geometries can develop as fluids propagate downward in porous media under variably saturated conditions. Unstable flow conditions are thought to cause the development of discrete fingers in the wetting front instead of a uniform-plane wetting front (Glass, Steenhusi, and Parlange 1989). The development of persistent preferential pathways, which dominate or control the flow of fluids, is well documented in numerous field investigations (e.g., Rousseau, Kwicklis, and Gillies 1997; Eaton et al. 1996; Wood and Norrell 1996; Neretnieks 1993). These observations appear to contradict the commonly used assumptions for employing macroscale continuum concepts of flow and transport in variably saturated media. Furthermore, available characterization and monitoring methods cannot completely identify these localized and persistent preferential pathways. Chemical and biological transformations may significantly alter water chemistries between the zones of preferential flow pathways and the rest of the media.

Even if the data were available for properly identifying and characterizing all localized preferential fast flow paths, modeling water movement in fractured media or in porous media exhibiting preferential flow at the field scale is computationally not feasible because of the numerically intensive effort required to represent the system at multiple scales of the flow. Either the modeling must be done on a scale of capillary forces or the basic problem needs to be reformulated. Developing a new formulation or improving existing formulation of the conceptual model of flow (e.g., by representing film flow, weep flow, or funnel flow) appears to be a promising alternative to using conventional approaches in systems in

which preferential flow exists. One formulation being attempted at the INEEL is to use the concepts of chaotic flow to approximate the underlying processes.

Faybishenko et al. (1998) proposed the development of physically based conceptual models on a hierarchy of scales. This approach is based on field investigations that were conducted in the vadose zone of the Snake River Plain. They found that, at each scale of investigation, different models can be used to describe flow processes on different scales, with no apparent scaling principles evident. At a smaller scale, centimeter to meter, flow apparently behaves in primarily chaotic fashion, while at a larger scale, 10 to 1,000 m, deterministic and stochastic analyses may represent the system. However, additional work is required in this area to fully define the transition between chaotic and stochastic representation and to develop deterministic-chaos based analyses.

Recent research at the INEEL of potential applications of deterministic chaos theory to fluid flow in variably saturated fractured basalt suggests that consideration of alternative approaches for quantifying flow and transport may be justified by long-term benefit. The alternative approaches, use of chaos theory in this case, differ significantly from the conventional methods based on volume averaging and Richards' equation used today. Figure D-11 is return map or pseudo-phase space diagram of data from the small-scale Hell's Half-Acre Experiment. The attractor defined in the figure represents the possible realizations for the point under investigation. Deterministic-chaos theory suggests that the attractor defines the possibilities of drip intervals for this location. Though the interval cannot be predicted at any given time, the possible range of outcomes can be bound. Transferring this understanding to vadose zone infiltration applications will require significant work. However, the potential benefits are clear. If an attractor can be defined for a vadose zone system, then the nonlinear, hysteretic processes of the vadose zone need not be defined because the system attractor could determine the full range of possible outcomes for the system.

An incorrect conceptual model of the physics of water transport can lead to significant errors in the development of mathematical and numerical models. Many aspects of the conceptual model of flow and transport through the INEEL vadose zone need further development. However, further development is limited by a lack of a good, physically based understanding of the physics of flow through the vadose zone. The INEEL, as well as many other semiarid sites with fractured rock vadose zones, does not have an adequate description of the preferential flow pathways and the continuity of mass transport between geologic units. In unsaturated zone flow and transport modeling currently, soil and fractured rock are treated mathematically as equivalent porous media units and the fluid flux between units is proportional to the hydraulic gradient. The equivalent approach fails to acknowledge that under preferential flow conditions, the wetting front penetrates the profile to significant depths through a small cross-sectional area bypassing the intervening pore space in the basalt matrix. Preferential flow results in an increased potential of groundwater contamination compared to uniform infiltration.

Further compounding the preferential fracture flow dilemma, is the inability to characterize the subsurface in sufficient detail and to provide the necessary parameters in sufficient detail. Preferential flow implies that only a few fractures and perhaps only a portion of those fractures are contributing to the transport of water. The current trend is to drill vertical boreholes to intersect with an active fracture and to monitor the borehole to document infiltration arrival. Clearly, this monitoring method will give limited and probably biased data.

Furthermore, the correct governing transport equation must be used in water transport models. The current trend to reduce the large uncertainties associated with the predictions of models is to develop more complex models, made possible by recent advances in computational ability (Jarvis 1994). However, simply increasing the complexity of the model structure by adding more parameters (which are

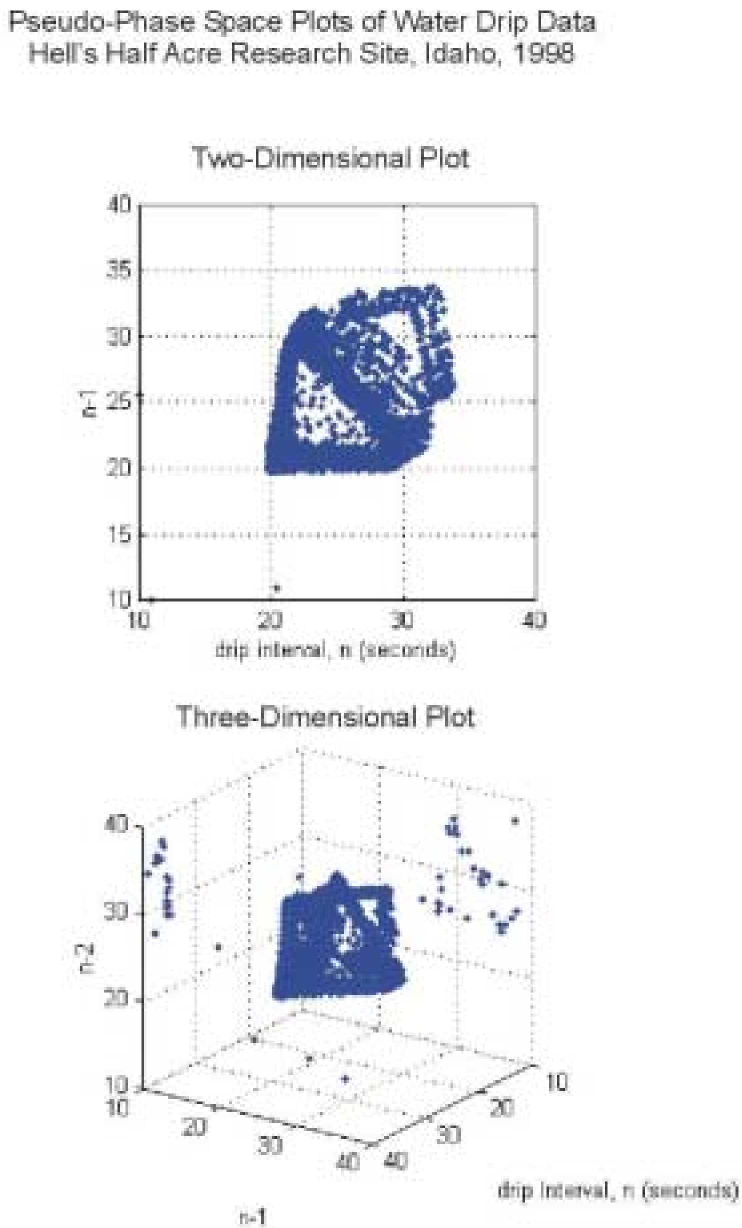

Figure D-11. Pseudo-phase space diagram of data from the small-scale Hell's Half-Acre Experiment.

extremely difficult to measure and identify) may not be the best approach (Tindal and Kunkel 1999). Alternative models should be evaluated.

D3.10.2 Deficiencies

- No generally accepted description exists of the mechanisms controlling flow in partially saturated fractures. The deficiency includes both the lack of a mathematical representation of the physics of flow and the parameters needed to describe the flow.

- The water transport between fractures and a porous matrix is poorly understood.

D3.10.3 Recommendations

The following activities would significantly advance the understanding of physics of flow at the INEEL:

- Examine the applicability of existing alternative physics of flow conceptual models for partially saturated fracture flow

- Develop alternative physics of flow conceptual models to partially saturated fracture flow

- Conduct carefully controlled hypothesis-based integrated field and laboratory tests to more accurately examine the physics of fluid movement in preferential flow settings in the vadose zone.

- Develop a consistent process of selection of model aspects based on modeling objectives. Assumptions or parameter values for the INEEL models are sometimes based on conservatism as opposed to technical grounds. Two separate models should be presented, if necessary, to ensure that one is conservative and that one provides best estimates based strictly on technical grounds and current knowledge.

D3.11 Source Term

D3.11.1 Summary

Models of contaminant transport through the vadose zone require source term input data, typically expressed as a flux of contaminants into the vadose zone. The accuracy of the source term data is often the most important factor affecting the overall accuracy of estimated risks associated with buried waste. Specialized source term codes such as Disposal Unit Source Term (DUST) (Sullivan 1993) and Breach, Leach, and Transport (BLT) (Sullivan et al. 1996; Sullivan and Suen 1989; MacKinnon, Sullivan, and Kinsey 1997) have been developed to generate source term input for the models. The models rely on empirically derived, lumped parameters (e.g., distribution coefficients) to describe important physical and chemical processes, reflecting the limited understanding of these processes. A lumped parameter is a measurable quantity that may be affected by a number of causes whose influences cannot be resolved independently.

After burial, waste interacts with the surrounding backfill material, resulting in the release of contaminants to the vadose zone. The interactions that occur in and near the buried waste are dependent on both the conditions in the backfill and the properties of the waste.

The near-field environment is the region of disturbed soil around and including a waste form, such as the backfill within an auger hole or trench, that is affected by the waste form to comprise a distinct hydrological and chemical environment. Chemically and hydrologically, the near-field environment likely changes over time, and because of the different radiological half-lives (and if they are known, chemical degradation rates), different contaminants will be released under different near-field conditions. For example, hydrologically, the most significant tritium releases from the beryllium blocks buried at the RWMC Subsurface Disposal Area probably occur within a decade of burial, when the soil disturbance caused by augering and backfilling still significantly affects vapor and probably liquid movement. However, the most significant ^{14}C releases (from a risk assessment point of view) may occur a hundred years after burial, at which time the backfill material may have the same hydrological characteristics as the surrounding soil. Again, using the buried beryllium as an example, the chemistry in the near field is affected currently by the presence of $MgCl_2$ (that is transported by liquid flow, a hydrological influence), the potential for galvanic corrosion because of the proximity of the beryllium blocks to their carbon steel containers, and the effect on the ^{3}H release rate caused by accumulation of the beryllium corrosion products. The processes occurring in the near-field environment control contaminant release to the general vadose zone and must be better understood to reduce uncertainty in the source term.

D3.11.2 Deficiencies

The reliability of source term estimates is limited by inadequate understanding of the processes causing waste-containment failure and the resulting mobilization of contaminants from waste forms.

D3.11.2.1 Inadequate Understanding of Near-Field Hydrology. Near-field hydrology may be generally understood in terms of the hydrology of the general vadose zone; however, the differences between the near-field environment and the vadose zone, some of which are described below, must be addressed.

- The variability of water flow on the scale of individual waste containers is more significant in the near field. The extent of container and waste-form contact with groundwater substantially affects the release of contaminants, and degradation of the container probably (almost certainly in the case of subsidence) affects water flow near or through the container, possibly changing its degradation rate and the rate of contaminant release.

- Container and backfill material is relatively non-uniform in the near-field environment compared to the general vadose zone environment. Appropriate measurement and model scales must be determined to adequately characterize and model the near-field environment.

- The soil porosity and permeability of the near-field environment differ from the general vadose zone environment because of the structural disturbance of the soil caused by excavation and backfilling, altering the hydrology and vapor transport characteristics of the near-field environment (Shakofsky 1995). Source term models must account for the effects of these altered characteristics as they affect transport in the near field, and measurement programs must be designed to characterize the near-field hydrology to avoid model and parameter errors caused by improper application of general vadose zone.

- The fractions of volatile contaminants (particularly ^{3}H, ^{14}C, and volatile organic compounds) released to the atmosphere from the near-field environment are unknown. Volatile contaminants in proximity to the soil/atmosphere interface have a relatively high probability of escaping to the atmosphere, and are more likely to be affected by seasonal weather changes. It is particularly important to look at these effects in the near field because field measurements have shown the disturbed soil to be preferential flow paths for gas phase transport (Ritter and McElroy 1999).

- Some proposed remediation technologies require grouting or vitrifying waste in situ with the intention of providing greater confinement of contaminants through modification of the geochemical and physical conditions in the near field. The ways in which these treated waste forms and containers would modify the near-field hydrology and the hydrology of the adjacent and underlying vadose zone are unknown.

D3.11.2.2 Inadequate Understanding of the Behavior of Waste Forms and Containers. At the INEEL, the primary waste materials are those typical of chemical industrial processes and small but potentially significant amounts of waste generated during research and development. Most of these waste materials have been buried uncontained or contained in wooden boxes, steel drums, or steel boxes. The expected lifetime of these commonly used containers is on the order of a few years to decades. Volatile organics released from early-failing containers may have accumulated in the near-field environment and exert an influence on subsequent diffusional releases and transport. The lifetimes of these containers are comparable to the human health risk summation period used for risk assessment. Therefore, the temporal distribution of container failures can have a substantial effect on the outcome of a risk assessment. Understanding of the behavior of the existing containers and waste forms and estimating source terms is deficient in the following areas:

- The fractions of volatile contaminants released by diffusion and advection from partially failed containers are unknown.

- Kinetics and spatial characteristics of the container failure process are unknown.

- The fraction of a contaminant’s total inventory that may exist in highly mobile forms is unknown. The uncertainty is particularly important because a relatively small fraction of the total inventory can cause most of the risk (as summed for exposure over a 30- or 70-year period) associated with the inventory.

- The chemistry of the near-field environment (e.g., the oxidation-reduction potential and solubility effects) may significantly affect the rate of migration to the general vadose zone. The release of contaminants into solution depends on the chemical environment at the surface and within the waste form. Disposal containers and waste forms can modify substantially the near-field chemistry and, therefore, contaminant release rates. In situ treatment of waste can have a profound effect on the near-field chemistry (e.g., grouting mechanically stabilizes waste but also can cause a nearly complete alteration of the chemical environment for release of contaminants).

D3.11.2.3 Limitations of Analysis Methodologies. The DUST source term code (Sullivan 1993) implements a relatively simple model that reflects the limitations of current knowledge of transport in the near field. The DUST code models releases caused by corrosion and dissolution, diffusion, or surface washoff and also models transport by diffusion or advection in a single phase in one dimension. Current source term (and vadose zone transport) models treat water flow through the near-field environment as a spatially uniform process; however, water flow is more likely to be non-uniform, event driven, and episodic. The source term model must account for the effects of the localized preferential, episodic flow, which may occur during runoff periods or during flooding events. In addition, the behavior of contaminants (e.g., the reaction capability of a contaminant to form other species or association with colloids) during periods of relative immobility also may cause important changes in their mobility.

D3.11.3 Recommendations

- Conduct laboratory-scale experiments to evaluate model parameters that are relatively insensitive to scale and which may be evaluated adequately at a relatively small scale. If necessary, field-scale experiments should be conducted to evaluate parameters that have large-scale spatial dependency.

- Conduct a detailed study of near-field processes affecting the source term. The study would improve modeling of contaminant migration from existing buried waste. The timing for such a study is critical because various treatment and remediation methods for this waste are being considered for use at the INEEL. A better fundamental understanding of near-field processes can be used to develop effective treatment and remediation methods. Current INEEL projects requiring source term modeling include the INTEC Tank Farm closure (DOE-ID 2000), the Organic Contamination in the Vadose Zone (OCVZ) project (Chatwin et al. 1992), and the Waste Area Group 7 comprehensive remedial investigation/feasibility study for waste disposed of in the SDA pits and trenches (Becker et al. 1998).

- Characterize water movement in the near field. The characterization would require instrumenting containers, waste forms, and backfill material within a few centimeters of the containers, as well as at more distant points within the disturbed backfill. The use of tracers should be considered. Some possible tracers that could be used include (^{3}H as CFA water or a nonhazardous, stable, volatile organic chemical). The objectives of water movement characterization would include the following:

    - Testing the representativeness of current moisture monitoring of conditions in the near field

    - Developing a realistic model of water movement through or at the surface of waste

    - Defining the appropriate conditions for bench-scale tests of waste-material properties

    - Estimating (with tracers) the fractions of volatile species migrating to the atmosphere from buried waste.

- Characterize geochemical processes that occur in the near field that influence the mobilization of contaminants. These processes include the following:

    - The chemical capability of contaminants to form more- or less-mobile species

    - Facilitated transport (i.e., the association of contaminants with colloids)

    - Corrosion processes as they affect buried activated metal objects and containers

    - Characteristics of grout and waste treated by in situ vitrification

    - Characteristics of water movement around waste treated by grouting or in situ vitrification.

- Refine analytical methods and models to account for advances in understanding of the processes that are found to substantially affect contaminant releases. A major objective for further study of the release of contaminants from waste forms is to improve the accuracy of source term codes such as DUST. More advanced source term codes should include features that allow more realistic modeling of near-field hydrology.

- Improve understanding of the following processes that would affect releases from grouted or in situ vitrification-treated waste:
  - The influence of the chemical environment within the grouted or glassified waste form on mobility of contaminant species
  - The relative importance of diffusional and dissolution-limited releases from grouted or in situ vitrification-treated waste in the initial monolithic form and as cracking and degradation progress
  - The effects of waste treatment on hydraulic properties within the treated waste at interfaces between treated waste and the surrounding medium and in cracks or other openings through the treated waste.

D3.12 Contaminant Vapor Phase Transport

D3.12.1 Summary

Limited vapor phase transport studies have been conducted at the INEEL notwithstanding that vapor phase transport can be the dominant transport mechanism for organics and radionuclides in arid environments. Most of the INEEL effort has been associated with the OCVZ extraction system remediating carbon tetrachloride (CCL_4), trichloroethylene (TCE), trichloroethane (TCA), tetrachloroethylene (PCE), and chloroform (CF) at the RWMC. Results of these investigations indicate that the CCl_4 vapor has been vertically transported causing concerns about groundwater contamination. This investigation also indicated that the shape of the plume is approximately 10 times as wide as it is deep. Along with the vapor phase organic contamination at the RWMC, ^{14}C and ^{3}H have been detected in the gas phase near the beryllium blocks buried in SDA and in the underlying 110-ft interbed (also referred to as the B-C interbed).

The RWMC is not the only location at the INEEL with the possibility of significant vapor phase transport. Volatile contaminants have been disposed of in the Central Facilities Area Landfill and may be a threat to groundwater. Trichloroethylene was directly injected into groundwater at Test Area North. Off-gassing to the overlying vadose zone may be an additional transport mechanism.

D3.12.2 Deficiencies

- The influences of barometric pressure on vapor movement at the INEEL, both horizontally and vertically are not known.
- The range of diffusion coefficients of surface soils at the INEEL has not been measured. It has been hypothesized that a significant fraction of the CCl_4 disposed of at the RWMC has diffused to the atmosphere. This estimate was made using several assumptions including an estimated diffusion coefficient.
- The influence of air injection during well drilling on plume movement is not well understood. The drilling of wells using air rotary drilling rigs may have significantly spread the plume.

- The large database of pressure readings taken at the RWMC has not been analyzed to develop pneumatic permeabilities to allow a more realistic prediction of OCVZ active soil vapor-extraction system on vapor movement.

- The process of vapor-liquid-solid partitioning, and fracture-matrix diffusion interaction is poorly understood. Vapor partitioning into the liquid and solid phases and vapor diffusion into the basalt matrix both will affect the efficiency of the OCVZ remediation effort. Present modeling assumes that equilibrium conditions exist between the three phases. Furthermore, parameters used to describe these processes are estimated.

- The U.S. Geological Survey (USGS) measured trace levels (ppt) of chlorinated solvents in shallow (at a depth of approximately 2 ft) vapor extraction ports around the SDA. The concentration gradients decrease with distance from the SDA and are detectable for a radius of several miles. The USGS speculated that vapors migrate horizontally in the vadose zone through horizontal high permeable pathways (e.g., lava tubes). However, this migration process has never been confirmed.

- The temporal and spatial flux of contaminants to the atmosphere is not adequately understood.

- Degradation of the vapor phase organic contaminant may occur. The mechanism and rate of the possible degradation are unknown.

D3.12.3 Recommendations

- Quantify the effects of barometric pressure changes on the transport of soil vapor at the INEEL.

- Quantify surface vapor fluxes of volatile organic compounds and other gas-phase contaminants to gain ranges of diffusion parameters in surface soils.

- Perform a modeling study to assess the effects of using air rotary drilling techniques that inject large quantities of air into rubble zones at the INEEL.

- Analyze the existing database and use inverse modeling to estimate permeability parameters at the OCVZ site.

- Identify the major processes retarding the cleanup of the organic contaminants at the OCVZ site.

- Develop and test a conceptual model of the transport mechanisms to adequately explain the USGS far-field soil-gas sampling results.

- Perform a literature search of the degradation processes of organic contaminants in fractured rocks followed by small-scale laboratory experiments to confirm that these processes occur at the INEEL. Use these experiments to develop initial estimated parameters for predictive studies.

D3.13 Integration

D3.13.1 Summary

In an attempt to integrate vadose zone studies at the INEEL, an effort supported by the INEEL Environmental Restoration Program Office is under way to develop an overall strategy to create an INEEL Vadose Zone Science and Technology Program Office. The charter of this office will be defined by the INEEL vadose zone roadmap, for which this document is a key element. A peer review of this deficiencies document by salient vadose zone experts from the INEEL, universities, and other DOE laboratories will occur at a workshop to be held during October 1999 as described in Appendix D.

Currently, vadose zone data are collected and funded at the project level. The establishment of the Vadose Zone Program Office would allow coordination of efforts for enhanced characterization, sustained vadose zone monitoring, and vadose zone research. The Program Office also would oversee the incorporation of new and innovative science and technologies into INEEL vadose zone projects and ensure that standardized methodologies and procedures are used to characterize and monitor the vadose zone. To meet specific vadose zone needs, the Vadose Zone Program Office would implement a network of advanced vadose zone monitoring stations in key locations at waste sites to collect both chemical and hydrologic data routinely for a sustained period of time (a minimum of 10 years). In addition, the Vadose Zone Program Office could coordinate research activities among the U.S. Geological Survey, site contractors, and universities to ensure that needs and uncertainties about the vadose zone are addressed.

D3.13.2 Deficiencies

D3.13.2.1 Lack of Coordination and Integration. The primary deficiencies in the current vadose zone characterization and monitoring at the INEEL are that data are collected on a project level and that the transfer of knowledge, data, and technologies is largely by informal communication. In addition, decisions to stop monitoring are made by individual projects without regard to impact on other projects. This lack of coordination has led to a discontinuous data set from the mid 1970s despite monitoring capabilities because monitoring program starts and stops based on individual project requirements or schedules. Also, the start and stop data collection has led to critical data not being collected during wet periods because monitoring was terminated. The current vadose zone efforts have illuminated an overarching lack of coordination between projects and between programs as well as deficiencies in the ability to disseminate information and data. The ability to track programmatic needs for vadose zone research, characterization, and monitoring does not currently exist.

D3.13.3 Recommendations

An INEEL Vadose Zone Science and Technology Program Office is needed to coordinate sampling, enhance communication and transmit data to end users. If funded, this office will provide integration between site programs and ensure complete data collection and model verification. This office also is needed to oversee the incorporation of new and innovative science and technologies into INEEL vadose zone project approaches and ensure that standardized methodologies and approaches are used to characterize and monitor the vadose zone. In addition, the establishment of this program should lead to reduced resource requirements necessary to conduct vadose zone characterization and monitoring at the INEEL and produce cost savings. Some of the specific needs that need to be addressed include the following:

- Incorporate vadose zone monitoring as an integral part of the assessment and cleanup effort for all major operable units. Currently, levels of vadose zone characterization and monitoring are inconsistent from one operable unit to the another. For instance, a limited effort has been expended for vadose monitoring at Waste Area Group (WAG) 7, the RWMC, yet virtually nothing has been done to collect vital vadose zone data at WAG 3, the INTEC.

- Coordinate and integrate vadose zone efforts between WAGs and standardize characterization and monitoring methods. An organized effort, funded for several years, could be used to support the development of nested projects where step-wise progress is made in vadose zone knowledge by causing the results from one test to feed into the next test at another WAG.

- Improve the collective INEEL ability to predict contaminant migration and in particular actinide mobility in the vadose zone. The observations of plutonium and americium in samples taken from interbeds and groundwater at the INEEL suggest that actinide mobility is greater than normally assumed. Such mobility has also been observed at Los Alamos National Laboratory, the Nevada Test Site (Discover 1999), the Hanford Site (GAO 1998), Clemson University (Newman et al. 1995), and in field- and laboratory-scale experiments conducted at the INEEL (e.g., Wood and Norrell 1996).

- Apply innovations in vadose zone characterization, monitoring, modeling, and remediation to all ongoing projects at the INEEL.

- Implement a coordinated effort in landfill cap analysis. This effort would including cap modeling, infiltration monitoring at currently capped sites, and use of the three existing facilities, the Simulated Waste Burial Trench Caps, the Protective Cap/Biobarrier Experiment, and the Engineered Barrier Test Facility, to develop reliable predictions of long-term cover performance as well as estimates of net infiltration on disturbed sites at the INEEL.

- Establish closer ties between the INEEL and other DOE sites to facilitate the exchange of site characterization and vadose-zone transport modeling efforts. The INEEL vadose zone efforts would benefit from more frequent interactions with peers at other western DOE sites (e.g., the Hanford site, Los Alamos National Laboratory, Yucca Mountain, and the Nevada Test Site) because workers at these sites are currently grappling with many of the same site characterization, monitoring, and modeling challenges.

- Evaluate past vadose zone characterization activities, remedial actions, and monitoring at all INEEL sites and at similar sites at other western DOE facilities to determine the current best solution for a variety of sites. A goal of this effort would be to establish a knowledge base from which to direct additional research on monitoring and characterization.

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Appendix E

Attendees at the October 1999
Idaho National Engineering and Environmental Laboratory
Vadose Zone Workshop

Appendix E

Attendees at the October 1999 Idaho National Engineering and Environmental Laboratory Vadose Zone Workshop

The attendees at the Idaho National Engineering and Environmental Laboratory Vadose Zone Workshop in Idaho Falls, Idaho, October 20 and 21, 1999, are listed below.

Table E-1. Attendees at the Idaho National Engineering and Environmental Laboratory Vadose Zone Workshop.

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Table E-1. (continued).

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